DELHI COLLEGE OF ENGINEERING

LIBRARY

R

CLASS NO. 621.31

BOOK NO. KIM

ACCESSION NO. 67825

DATE DUE

For each day's delay after the due date a fine of 3 P. per Vol. shall be charged for the first week, and 25 P. per Vol. per day for subsequent days.

Borrower's No.	Date Due	Borrower's No.	Date Due

POWER SYSTEM STABILITY

Volume II

Power Circuit Breakers and Protective Relays

By Edward Wilson Kimbark

POWER SYSTEM STABILITY

Volume I—Elements of Stability Calculations
Volume II—Power Circuit Breakers
and Protective Relays

Volume III—Synchronous Machines

ELECTRICAL TRANSMISSION
OF POWER AND SIGNALS

POWER SYSTEM STABILITY

Volume II
Power Circuit Breakers and Protective Relays

Edward Wilson Kimbark, Sc.D.
Dean, School of Engineering
Seattle University
Fellow A.I.E.E.

JOHN WILEY & SONS, Inc.
New York • London • Sydney

COPYRIGHT, 1950
BY
EDWARD WILSON KIMBARK

All Rights Reserved

Reproduction or translation of any part of this work beyond that permitted by Sections 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc

16 15 14 13 12

PRIN[illegible] IN THE U[illegible]TED STATES OF AMERICA

ISBN 471 47619 6

To my wife

RUTH MERRICK KIMBARK

PREFACE

This is the second volume of a three-volume work on power-system stability intended for use by power-system engineers and by graduate students. It grew out of lectures given by the author at Northwestern University in graduate evening courses on power-system stability and on power-system protection.

The present volume covers power circuit breakers and protective relays, including material on rapid reclosure of circuit breakers and on the performance of protective relays during swings and out-of-step conditions. Such material belongs in a work on stability because the most important means of improving the transient stability of power systems are (1) faster clearing of faults by means of faster circuit breakers and relays and (2) rapid reclosure of circuit breakers. It is expected, however, that the publication of this material in a separate volume will make it more useful to persons who are interested in power-system protection even though they may not be particularly concerned with the subject of stability.

One of the newest aspects of protective relaying, the performance of relays during swings and out-of-step conditions, is comprehensively treated here by both algebraic and graphical methods. Such material has not been available heretofore in book form. The same can be said of most of the material on rapid reclosure of circuit breakers, another subject of fast-growing importance. Both three-pole and selective-pole tripping and reclosure are discussed, including their effects on system stability.

The discussion of circuit breakers and, especially, of protective relays almost necessitates references to proprietary products; and this has been done without bias for the products of any manufacturer.

Volume I, which appeared in 1948, covers the elements of the stability problem, the principal factors affecting stability, the ordinary simplified methods of making stability calculations, and illustrations of the application of these methods in studies which have been made on actual power systems.

Volume III will endeavor to give the reader a deeper understanding of power-system stability than that afforded by Volume I alone. It will deal with synchronous machines, excitation systems, damping, and saturation.

I wish to acknowledge my indebtedness to the following persons:

To my wife, Ruth Merrick Kimbark, for typing the entire manuscript and for her advice and inspiration.

To J. E. Hobson, W. A. Lewis, and E. T. B. Gross for reviewing the manuscript and for making many suggestions for its improvement.

To engineers of the General Electric Company and of the Westinghouse Electric Corporation for reviewing certain parts of the manuscript pertaining to products of their companies, and especially to Mr. W. M. Leeds, who reviewed the material on power circuit breakers and criticized it very constructively.

To manufacturers, authors, and publishers who supplied illustrations or gave permission for the use of material previously published elsewhere. Credit for such material is given at the place where it appears.

EDWARD WILSON KIMBARK

Evanston, Illinois
July, 1950

CONTENTS

CHAPTER PAGE

VIII Fault Clearing—Power Circuit Breakers 1

IX Fault Clearing—Protective Relays 67

X The Influence of Swinging and Out-of-Step Operation upon Protective Relays 158

XI Rapid Reclosing 220

INDEX 279

CHAPTER VIII

FAULT CLEARING—POWER CIRCUIT BREAKERS

FAULT CLEARING

Rapid clearing of faults promotes power-system stability. As shown in Fig. 20 of Chapter VI, Vol. I, the transient stability power limit, or power which can be transmitted without loss of synchronism during a fault, is greater the more rapidly the fault is cleared. Indeed, increasing the speed of fault clearing is often the most effective and most economical way of improving the transient stability of a power system or of increasing its stability limit.

Rapid fault clearing is desirable for additional reasons. It lessens annoyance to electric-power customers from flickering of lamps due to voltage dips and from shutting down of motors through operation of undervoltage tripping devices. It also decreases the damage to overhead transmission-line conductors and insulators at the point of fault. Such damage is most likely to occur if the fault current is great: then, with slow clearing, conductors may burn down or insulators may crack from the heat of the arc, giving rise to a permanent fault. With rapid clearing, on the other hand, the conductor is hardly damaged, and the line can be put back into service immediately. The great majority of transmission-line faults originate as one-line-to-ground faults. High-speed clearing decreases the likelihood of such faults developing into more severe types, such as two-line-to-ground or three-phase, through the arc being carried by the wind from one conductor to another.

Since rapid fault clearing is so important for increasing stability and for other reasons, it is fitting to consider the circuit breakers and relays, the function of which is to clear faults. Circuit breakers serve to open the faulted circuit and thereby to sever it from the sound part of the power system. They are required to interrupt abnormally large currents. Protective relays serve to detect the presence of faults, to determine their locations, and to initiate the opening of the proper circuit breakers. To isolate a fault with the least interruption of service to customers and with the least shock to the synchronous machines, only the faulted circuit—and no other—should be disconnected. This requires the use of relays which will select correctly the circuit breakers that should be opened. In addition, both the relays and the circuit breakers should act as rapidly as possible consistent with selectivity. (It is better to open the right breakers with some delay than to open the wrong breakers immediately.)

Most of the faults on overhead transmission lines are caused by lightning. Such faults usually do no permanent damage. After the line has been disconnected by the circuit breakers the arc goes out, and in a short while the arc path becomes deionized and recovers its insulating strength. Then the line may be re-energized without causing the arc to restrike. Putting the line back into service immediately is advisable, not only to restore service to loads (if any) which are solely dependent upon the particular line, but also to render the system less vulnerable to any fault which may occur later. Furthermore, rapid reclosure of the circuit breakers, accomplished while the machines are still swinging apart in consequence of the fault, increases the restoring forces and thus increases the stability limit of the system. Manual reclosure is too slow to have any effect on the stability limit, but high-speed automatic reclosure has a marked effect. In particular, the stability limit of a single-circuit line which is the sole tie between two groups of synchronous machines is zero without high-speed reclosure but may be considerable if such reclosure is employed. The same is true of a double-circuit tie line in the event of faults involving both circuits at the same time if at least one of the two circuits has high-speed-reclosing breakers. Methods of analyzing the effect of high-speed reclosing on stability are considered in Chapter XI.

Speeds of circuit breakers and relays. For the reasons stated in the preceding section, high-speed clearing of faults is necessary or desirable in many cases, and the added feature of high-speed automatic reclosing is frequently desirable. Circuit breakers and relays, according to their speed and according to whether or not reclosing is employed, may be divided into the following classes:

1. Slow-speed circuit breakers and relays.
2. High-speed circuit breakers and relays.
3. High-speed reclosing circuit breakers and relays.

The usual fault-clearing times for all classes and the reclosing times for the last class will now be discussed. The clearing time is the sum of the relay time and the breaker interrupting time. The relay time is the elapsed time from the instant when a fault occurs until the instant when the relay contacts close the trip circuit of the circuit breaker. The breaker interrupting time is the elapsed time from this instant until the instant when the current is interrupted. It is the sum of the breaker opening time (the time required to part the breaker contacts) and the arcing time. Reclosing time is the elapsed time from the instant of energizing the trip circuit, the breaker being in the closed position, until the instant when the breaker arcing contacts touch on the reclosing stroke; it includes breaker opening time and time during which the breaker is open. All these times, if short, are customarily expressed in cycles on the basis of the usual power-system frequency of 60 cycles per second.

Slow-speed circuit breakers and relays. Before 1930 breakers having interrupting times of 15 to 30 cycles and relays having times of 6 to 120 cycles were generally used. The resultant clearing times were from 21 to 150 cycles. With such slow clearing, the power limits were but little higher than the limits with sustained faults. Many slow-speed breakers and relays are still in use where rapid clearing is not necessary.

High-speed circuit breakers and relays. As the importance of faster clearing to stability became recognized, higher-speed circuit breakers and relays were developed. In 1929, 8-cycle breakers were introduced; and, in 1930, 8 cycles became the standard breaker speed. Three-cycle breakers were first developed for the 287-kv. line from Boulder Dam to Los Angeles about 1935. In 1949, the standard interrupting time for 230-kv. breakers was 3 cycles; for 161-kv. and 138-kv. breakers, 3 or 5 cycles; for 115-kv., 5 cycles; and for lower voltages. 8 cycles. Undoubtedly, the trend toward higher breaker speeds will continue; 5-cycle and 3-cycle breakers may be expected to become more common, and breakers of even higher speeds will probably be developed.

Many of the slow-speed circuit breakers have been rebuilt or can be rebuilt to make them faster. At least 8-cycle operation, and often 5-cycle or better, can be obtained by rebuilding.

If both slow-speed breakers and slow-speed relays are used, the speed of clearing can usually be increased more economically by changing to high-speed relays than by rebuilding or replacing the circuit breakers.

Present high-speed relays operate in from 1 to 3 cycles. In most cases 1 cycle can be relied upon. The use of high-speed relays, therefore, gives a clearing time of 9 to 11 cycles if 8-cycle breakers are used, or 6 to 8 cycles if 5-cycle breakers are used. However, this clearing time cannot be achieved for all fault locations on a transmission line unless a pilot channel, such as carrier current, connecting the two ends of the line, is used to supplement the relays. Otherwise, a fault near either end of a line must be cleared in two steps—by high-speed opening of the breaker at the end near the fault (for example, 1 cycle relay time plus 8 cycles breaker time) followed by delayed opening of the breaker at the distant end (say, 15 to 30 cycles relay time plus 8 cycles breaker time). Although the final clearing time is long with this relaying scheme, the rapid opening of the first breaker materially improves the stability situation, for the fault is left connected to the system radially through the impedance of nearly the whole length of the line. Further improvement may be obtained—at additional expense, of course—by the use of a pilot-wire or carrier-current channel to secure simultaneous high-speed opening of the breakers at both ends.

Little, if any, increase in relay speeds over those now obtainable with carrier current can be expected because at least half a cycle of single-phase current and voltage appears to be necessary for obtaining reliable operation of the directional relay elements.

High-speed-reclosing circuit breakers and relays. High-speed reclosing has become common at the higher voltages, and the standard reclosing time of breakers for this service is 20 cycles. Such breakers are usually opened and closed by pneumatic mechanisms. Somewhat higher speeds of reclosure may be expected in the future, though the permissible speed is limited by the necessary "dead time" required for deionization of the arc path (see Chapter XI). High-speed carrier-pilot relaying having relay time of 1 cycle is always used with high-speed-reclosing breakers.

CIRCUIT BREAKERS

Circuit breakers and associated switchgear may be divided into four classes:[A11*]

1. Low voltage—up to 600 volts a-c. or 750 volts d-c.
2. Medium-low voltage and interrupting rating—2.3 to 15 kv., 25 to 500 Mva.[†]
3. Medium-high voltage and interrupting rating—15 to 34.5 kv., 500 to 2,500 Mva.
4. High voltage—46 kv. and over.

Low-voltage circuit breakers are used for light and power circuits in buildings and in industrial plants, for electric railways, and for low-capacity power-station auxiliaries. Nearly all of them are air circuit breakers.

---

[*] Superior letters and numerals refer to items in the list of References at the end of the chapter.

[†] Circuit-breaker ratings are discussed in a later section of this chapter.

Circuit breakers of the last three classes were once exclusively oil circuit breakers, but, since many air circuit breakers of these classes have been installed, the term *power circuit breakers* has been applied to both oil and air circuit breakers in these classes.

Medium-low-voltage circuit breakers are used in small power stations, including municipal and industrial plants, in steel mills, and for high-capacity auxiliaries in large power stations. Although many oil circuit breakers are still in service, the trend is toward air circuit breakers, especially those of the magnetic-blowout type.

Medium-high-voltage circuit breakers are found in important substations and in the generator-voltage circuits in large power stations. The commonest voltage class is 13.8 kv., and the commonest interrupting ratings are 1,000, 1,500, and 2,500 Mva. Here again, many oil circuit breakers are employed; but, since 1940, air-blast breakers, which had already been developed in Europe, have become widely used in the United States, most new installations being of this type. For 22-kv. and 33-kv. service, outdoor oil circuit breakers of the frame-mounted dead-tank type are still the commonest, but there is an increased trend toward indoor air-blast breakers. Water circuit breakers[H] have been used in Europe since 1930, and some development work has been done, particularly in Germany, on vacuum circuit breakers and others, but none of these types has found favor in the United States.

High-voltage circuit breakers are used on important transmission lines. (Incidentally, there is a notable trend toward the elimination of generator-voltage switchgear in large generating stations which do not have a large local load but which transmit bulk power over high-voltage transmission lines. In such stations each generating unit, consisting of a generator and a step-up transformer, is connected through a high-voltage circuit breaker to a high-voltage bus or, sometimes, to one high-voltage line.) In the high-voltage class, oil circuit breakers of the outdoor floor-mounted steel-tank type have remained in favor in the United States and have been greatly improved as to speed, interrupting capacity, and compactness. Low-oil-content porcelain-clad impulse circuit breakers have been employed to a lesser extent. High-voltage air-blast circuit breakers are in general use in Europe, and, though there are few of them in the United States at present (1950), it seems likely that their importance will increase.

High-voltage circuit breakers have large interrupting capacities and short interrupting times. The greatest interrupting rating increased from 2,500 Mva. in 1940 to 5,000 Mva. at 138 kv. and 10,000

Mva. at 230 kv. in 1948, and interrupting times of 3 and 5 cycles are standard.

The types of circuit breaker used in the high- and medium-high-voltage classes, being those of most concern in stability studies, will be described in some detail.

Oil circuit breakers—description. In oil circuit breakers, the current is interrupted in oil, which, by its cooling effect, helps to quench the arc that forms when the contacts part, and which, because of its insulating properties, permits closer spacing of live parts than would be permissible in air.

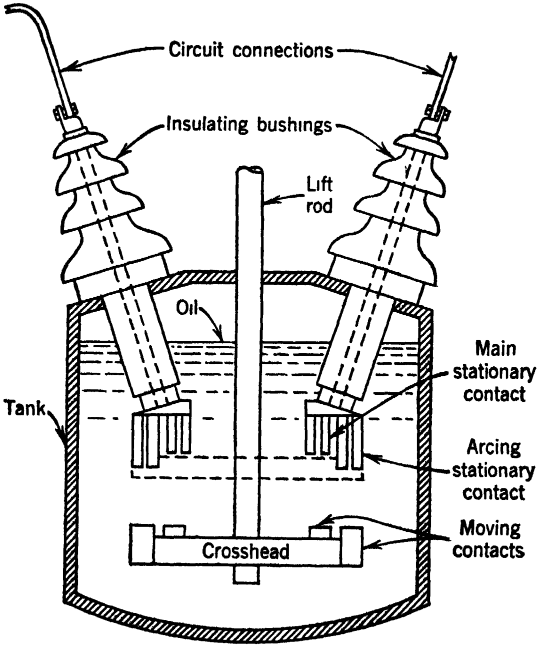


FIG. 1. Section of ordinary oil circuit breaker (contacts in open position).

The ordinary form of oil circuit breaker (Fig. 1) has one or more metal tanks filled with oil. The tanks have metal tops with insulating bushings through which the circuit enters and leaves the tank. To the lower ends of the bushings, beneath the surface of the oil, are attached stationary contacts. A crosshead carrying movable contacts bridges the gap between each pair of stationary contacts and completes the circuit when the breaker is closed; it is displaced (usually downward) from the bridging position when the breaker is opened. Renewable arcing contacts, which open after the main contacts and close before them, are usually provided to protect the main contacts from burning (Figs. 1 and 2).

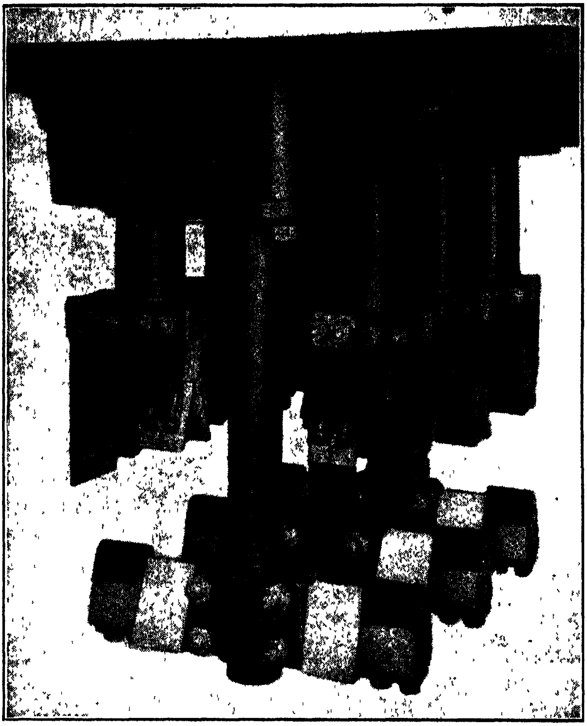


FIG. 2. Contact assembly of the oil circuit breaker of Fig. 3. The contacts are of the wedge type. The inner contacts are the main contacts; the outer ones, the arcing contacts. (By courtesy of the General Electric Company)

Three-pole breakers, used on three-phase circuits, may be built either with one tank (Fig. 3) or with three tanks (Figs. 4 and 5). At very high voltages, three tanks are generally used; however, one-tank breakers have been built for 138 kv.[131] The horizontal cross section of the tanks may be rectangular, oval, or round. Round tanks are used on breakers of high interrupting capacity, because they are best suited to withstand without deformation high internal pressures resulting from the formation of gas by the arc volatilizing the oil. Very large tanks (Figs. 5 and 6) rest directly on a foundation and have manholes for access, but smaller tanks (Figs. 3 and 4) are usually mounted on a steel framework and may be lowered to permit inspection and maintenance of the contacts. Indoor breakers are often placed in masonry (brick or concrete) cells or in steel cubicles. In metal-clad switchgear, the breakers have self-coupling disconnecting devices and the whole breaker is moved to connect it to or disconnect it from the circuit.

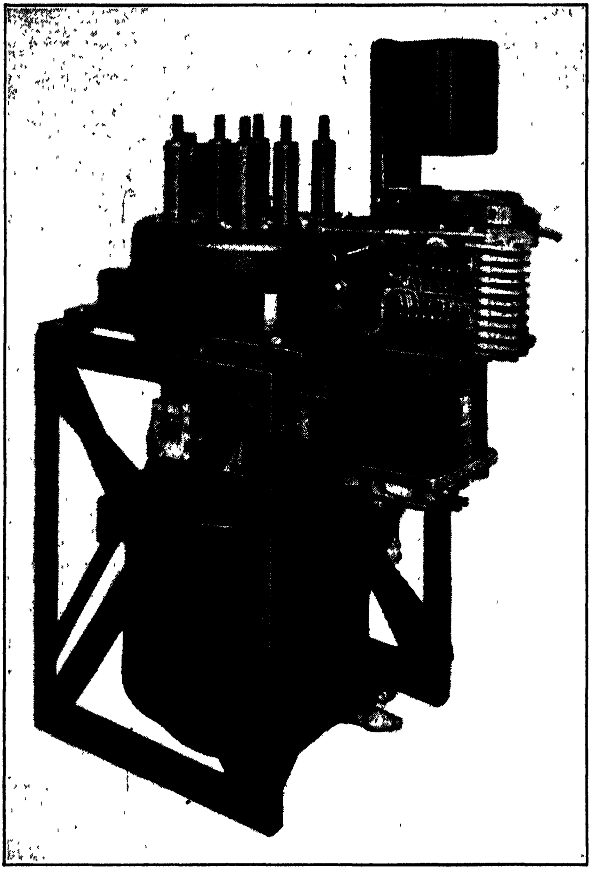


FIG. 3. Frame-mounted indoor oil circuit breaker with three poles in one tank. Rating: 15 kv., 600 amp., 250,000 kva. The round tank is divided by barriers into three compartments. (By courtesy of the General Electric Company)

The tanks are dead in most designs. However, there is one well-known line of medium-voltage indoor breakers in which the tanks are alive. (See Fig. 7.) The live tanks are placed in steel or masonry cells and rest on foot insulators, which insulate the tanks from the floor and also serve as bushings to bring connections to the breaker from bus compartments below the floor. In live-tank designs for high normal currents, the main contacts are usually in air, and only the arcing contacts are in oil.

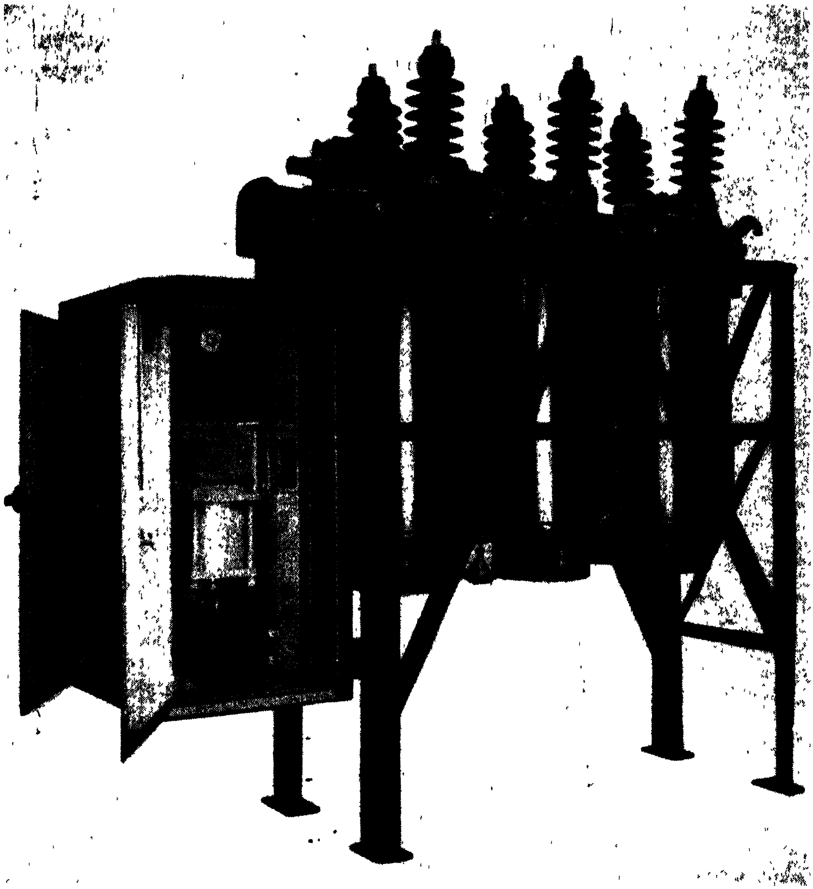


FIG. 4. Frame-mounted outdoor oil circuit breaker with three tanks. (By courtesy of the General Electric Company)

The moving contacts of a circuit breaker are mounted on operating rods made of resin-impregnated laminated wood or paper-base laminate. In the older and smaller breakers these rods extend through holes in the tops of the tanks to a common crossbar or to cranks on a common shaft, thus permitting group operation of all poles of the breaker. Such breakers are "nonoiltight." When they are called upon to interrupt large currents, oil may be thrown out of the holes for the rods. Modern breakers of moderate and high rupturing capacity are usually built with operating levers and cranks beneath the top of each tank (Fig. 8). Mechanical connection between the several tanks and the actuating mechanism is made through a horizontal pull-rod or crankshaft extending through bushed holes in the sides of the tank tops. This arrangement frees the space above the tanks from rods, crossbars, and other moving parts, thereby giving a neater appearance and increasing the clearances between live parts and grounded objects. The tanks may be made oiltight. The tanks of some breakers are equipped with separators or mufflers to allow the escape of gases formed during current rupture without allowing oil to escape (see Fig. 7).

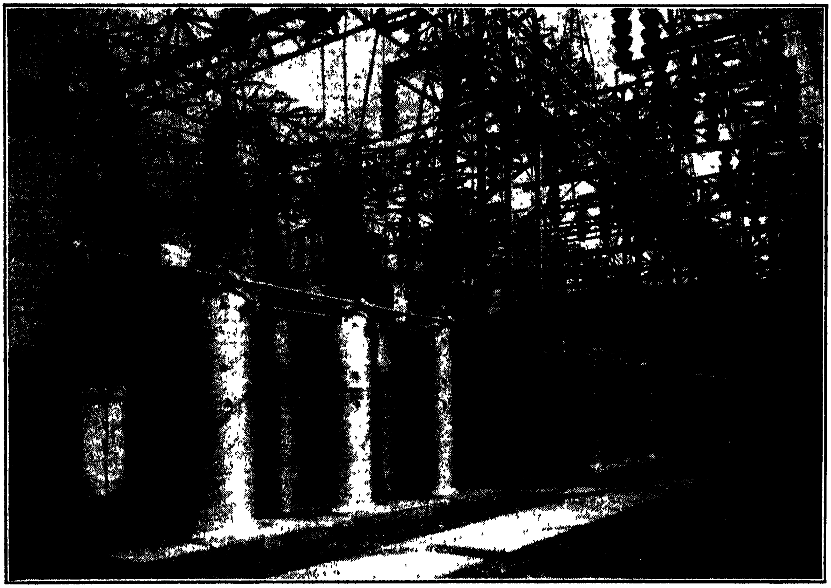


FIG. 5. An installation of floor-mounted outdoor oil circuit breakers. (By courtesy of Westinghouse Electric Corporation)

Circuit-breaker operating mechanisms and control systems. The moving contacts of a circuit breaker are opened by powerful springs and are held closed against the force of the springs by a latch or toggle which is easily tripped (Fig. 8). Thus a greater force is required to close the breaker than to open it.

Many small low-voltage circuit breakers are manually operated.

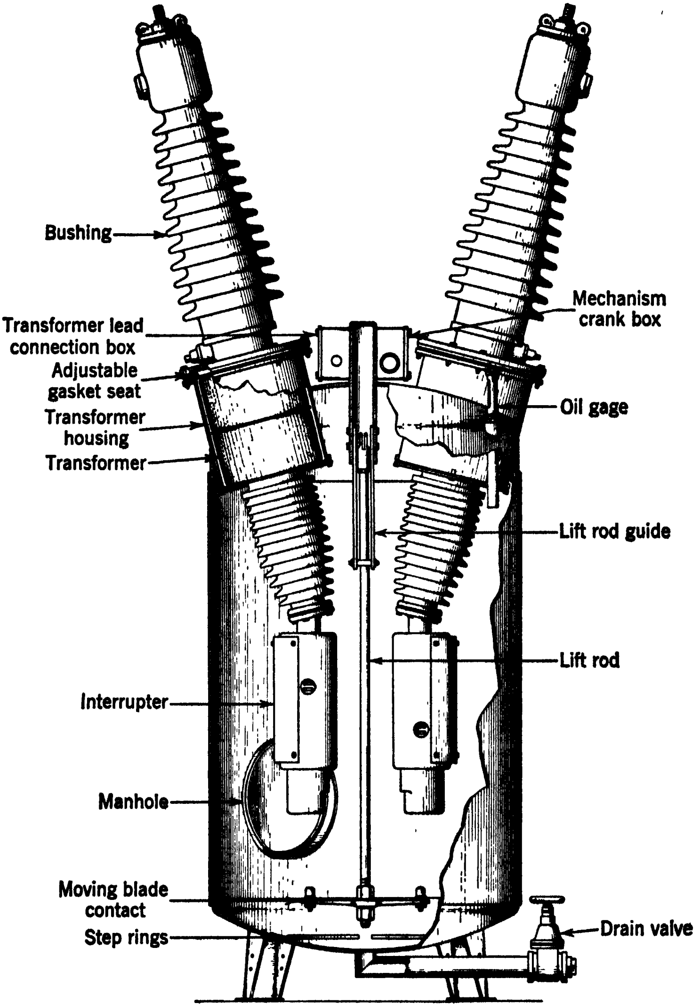


FIG. 6. Section of pole unit of 138-kv. floor-mounted outdoor oil circuit breaker. (By courtesy of the General Electric Company)

They are closed by means of an operating handle on the breaker itself or connected to it mechanically through rods and bell cranks, and they are tripped by releasing the latch either manually or electrically. Large circuit breakers, however, both because of the energy required to close them and because of the necessity for remote control, are always power-operated. The circuit breakers are frequently located at some distance from the switchboard where they are controlled: they may be outdoors, in another building, or on another floor. They may be either pneumatically or electrically operated.

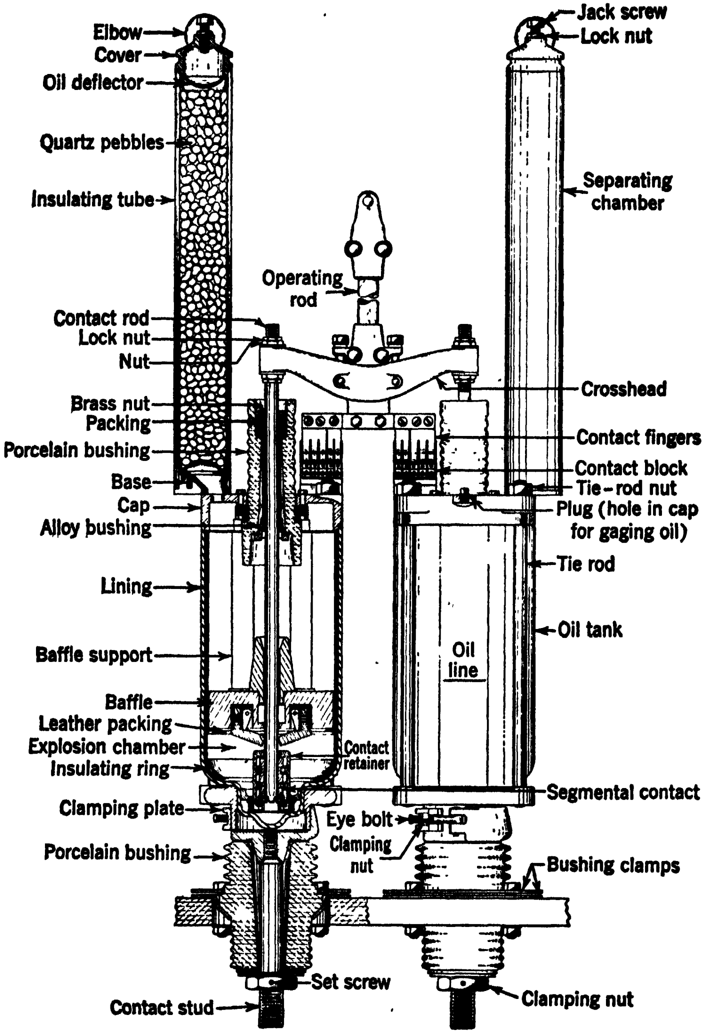


FIG. 7. Low-oil-content live-tank station-type oil circuit breaker. (By courtesy of the General Electric Company)

The standard method of electrical operation is to use two d-c.

solenoids (Fig. 8), a large one for closing the breaker and a small one for opening ("tripping") it. Power for operating the solenoids is supplied by a 125-volt or 250-volt storage battery, which is dependable in spite of possible failure of the a-c. power during faults. The closing coil requires from 10 to 300 amp. at 125 volts, depending upon the size of the breaker; the trip coil, from 4 to 25 amp.

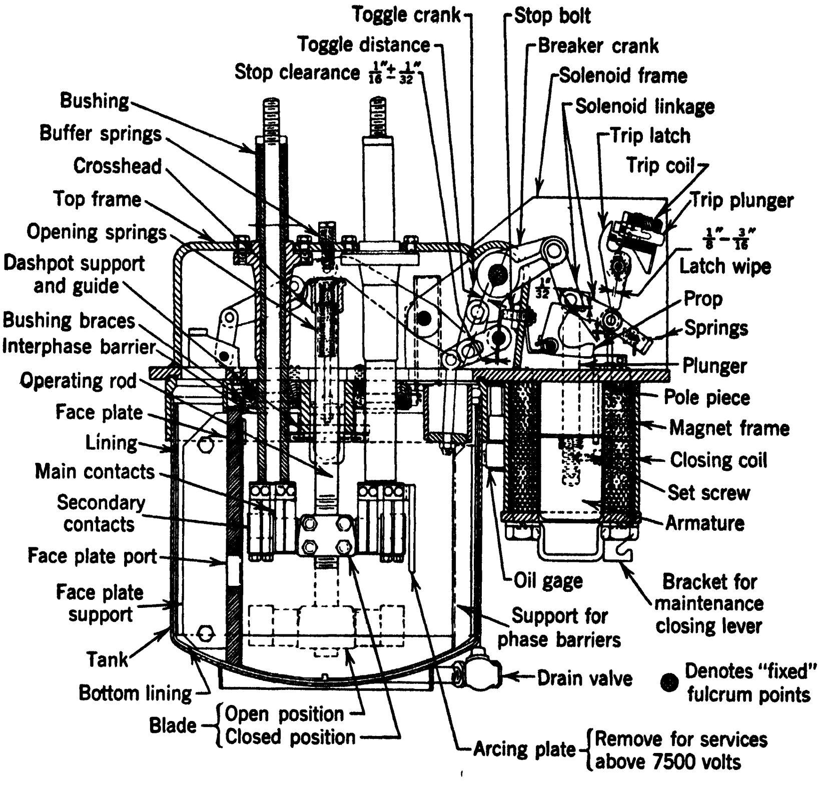


FIG. 8. Section of the oil circuit breaker of Fig. 3, showing solenoid-type operating mechanism. (By courtesy of the General Electric Company)

For routine switching, the trip coil and a relay which energizes the closing coil are controlled through switches mounted on the switchboard. For clearing faults, the trip coil is energized through contacts of the protective relays. Trip coils for fault clearing must be provided even on breakers which are operated manually for routine switching. Power-operated breakers have provision for manual operation for purposes of maintenance and adjustment only. No attempt should be made to use the manual operating device for closing high-capacity breakers on an energized circuit.

Another method of electrically closing a breaker is by means of a motor. One type of motor mechanism has a hardened steel cam which converts the rotation of the motor to a linear motion of great force, closing the breaker smoothly and without shock or overtravel at the end of the stroke. A second type utilizes centrifugal force to change the high-speed rotation of the motor to linear motion. A third type of motor-operated mechanism uses the motor to wind up or compress springs which, when released by a solenoid-operated latch, close the breaker. Some breakers are both opened and closed by motor-wound springs. Motor-operated mechanisms, as a rule, require less current than solenoids.

As a 125-volt storage battery is an expensive item for a small station, a-c. closing mechanisms are frequently used. For breakers customarily operated by means of solenoid mechanisms, each solenoid mechanism is provided with a copper oxide rectifier connected to the a-c. control source to provide the d-c. power for the closing solenoid. For motor-operated breakers an a-c. motor is used. When a-c. closing is employed, tripping for faults may be accomplished either with alternating current obtained from current transformers in series with the breaker or with direct current from a low-voltage storage battery.

Pneumatically operated mechanisms are used for air-blast breakers and for large, outdoor, high-voltage oil circuit breakers where high-speed reclosing is desired, or where it is desirable to conserve either control power or the amount of copper in the control leads. A typical pneumatic operating mechanism is described in Chapter XI.

Circuit-breaker operating mechanisms are equipped with a number of *auxiliary switches*, some of which are open when the breaker is open and are closed when the breaker is closed, others of which are closed when the breaker is open and are open when the breaker is closed. The auxiliary switches are used to control lamps on the switchboard for indicating whether the breaker is open or closed, to open the trip circuit after the breaker has been opened, to open the closing circuit after the breaker has been closed, and to perform other control functions as needed.

A circuit breaker is said to be *mechanically trip-free* if "the tripping mechanism can trip it even though (1) in a manually operated circuit breaker, the operating lever is held in the closed position; or, (2) in an electrically operated circuit breaker, the operating mechanism is held in the closing position either electrically or by means of an emergency closing lever."[‡] Preferably the tripping mechanism should be able to trip the breaker at any point of the closing stroke, making it unnecessary to complete the stroke before tripping can occur. An electrically operated circuit breaker is said to be *electrically trip-free* if

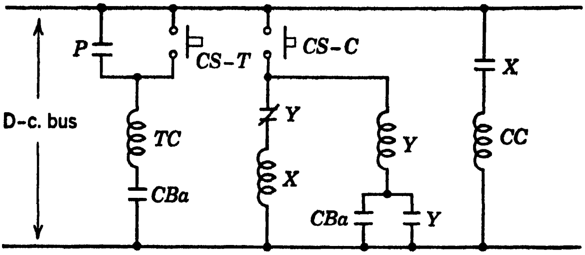


FIG. 9. Control circuits of a circuit breaker for making it electrically trip-free.

CBa	Auxiliary switch on circuit breaker, closed when breaker is closed.
CC	Closing coil of circuit-breaker mechanism.
CS-C	Control-switch closing contact.
CS-T	Control-switch tripping contact.
P	Protective-relay contacts, which close when fault occurs.
TC	Trip coil of circuit breaker.
X	Closing contactor.
Y	Releasing contactor.

"the tripping mechanism can trip it even though the closing control circuit is energized and the closing mechanism will not reclose it after tripping until the closing control circuit is opened and again closed. However, the breaker may be held closed by the emergency operating lever unless it is also mechanically trip-free."[§] It is desirable that an electrically operated breaker be both electrically and mechanically trip-free.

A typical control circuit for an electrically operated circuit breaker, including provisions for making the breaker electrically trip-free, is shown in Fig. 9. The trip coil *TC* is energized either by the contacts of the protective relays *P* or by the control switch *CS–T*. When the operator wishes to close the circuit breaker, he closes control-switch contacts *CS–C*, thereby energizing the coil of closing contactor *X*, the contacts of which, in turn, energize the closing coil *CC* of the circuit breaker. Assume that the control switch is held closed longer than necessary. As soon as the breaker closes, its auxiliary switches *CBa* close, one of which energizes the releasing contactor *Y*. The back contacts of *Y* open the circuit to the coil of contactor *X*, causing *X* to

[‡] Reference K4, rule SG50-448, and Ref. K6, sec. 4-5.9.1.

[§] Reference K4, rule SG50-449, and Ref. K6, sec. 4-5.9.3.

de-energize the closing coil. Overheating of the closing coil and unnecessary drain of the control storage battery are thus prevented. The front contacts of *Y* form a holding circuit which keeps coil *Y* energized as long as control switch *CS–C* is held closed, even though the breaker should be tripped by the protective relays, opening contacts *CBa*. Therefore, in such an event, the circuit to coil *X* is held open by back contacts *Y*, and the breaker will not be reclosed unless the operator first releases the closing switch *CS–C*, permitting *Y* to drop out, and then actuates it again.

Arc extinction. The arc in a circuit breaker is a column of hot, ionized gas. The breaking of the circuit by extinction of this arc occurs in two successive stages. In the first stage, the resistance of the arc increases to a value so high that the current is negligible, and, in the second stage, the dielectric strength of the arc space increases to a value so high that the arc will not be reignited by the circuit voltage. Increases of both resistance and dielectric strength of the arc are accomplished by lengthening and deionizing it. The lengthening of the arc is due mainly to the motion of the contacts, sometimes aided by magnetic-blowout effect and by arc splitters. Deionization of the arc is accomplished by cooling it, by bringing it into contact with solid surfaces where recombination of ions occurs, and by turbulent admixture of un-ionized material. In an air-blast circuit breaker, lengthening and deionization of the arc are effected by blowing a stream of air through the arc. In an oil circuit breaker, deionization of the arc is accomplished by contact of the arc with the oil, with metal or fiber plates, and with un-ionized gas generated by the decomposition of oil and fiber when heated by the arc. In oil circuit breakers of modern design, either the arc is moved through the oil, or, more usually, a stream of oil and gas is forced through the arc.

Extinction of an a-c. arc is much easier than that of a d-c. arc because the value of an alternating current normally becomes zero twice during each cycle. An a-c. circuit is broken by preventing the current from restarting after a normal current zero. In order to prevent the current from restarting, the dielectric strength of the arc space must be increased more rapidly than the voltage across this same space. The second stage of current interruption (increase of dielectric strength) is more important in breaking an a-c. circuit than the first stage (increase of arc resistance), although some increase of resistance is evidenced by increase of arc voltage and the hastening of the current zero by a very small fraction of a cycle.

One other feature of the first stage meriting some discussion is arc energy. Because the disturbances in a circuit breaker (such as the amount of oil decomposed and the pressure in the tank) when interrupting fault current increase with the energy of the arc, it is desirable to make this energy as low as possible. The energy depends upon the arc current, arc voltage, and arc duration. In order to make the arc energy as low as possible for a given current to be interrupted, the arc resistance should change from a very low value to a very high value as suddenly as possible. Although, ideally, the current ought to be interrupted at the first normal current zero after parting of the contacts, in some circuit breakers it is not interrupted until several cycles later. If the arc energy is to be small even though the arcing time is long, the arc voltage must be low during most of this time. Subjection of the arc to a blast of air or oil, although it increases the arc voltage, decreases the arc energy by decreasing the arcing time.

The air or oil blast also increases the dielectric strength of the arc space after a current zero. In order to prevent reignition of the arc, the dielectric strength of the space between the parting contacts must increase more rapidly than the voltage between contacts. This voltage, known as the *recovery voltage*, consists of voltage of the normal or generated frequency of the power system to which the breaker is connected, together with transient voltages of various natural frequencies (usually much higher than the generated frequency) dependent upon the amount and arrangement of the inductance and distributed capacitance of the system.

The recovery voltage of a simple single-phase circuit[C31] is illustrated in Fig. 10. Here R and L represent the impedance of a source (consisting of generators and perhaps also of transformers or lines), e_g is the voltage of the source, and C represents the stray capacitance of a line, cable, or bus near the circuit breaker. Initially the circuit breaker CB is closed, and the line-to-ground voltage e_C varies sinusoidally as shown by the dotted curve. Let a short circuit F occur at time t_1 when the voltage is a maximum. Voltage e_C vanishes, and a fault current i flows, which lags nearly 90° behind the voltage because the impedance of the circuit is predominantly inductive reactance. Suppose that the circuit breaker interrupts the current at its normal zero (time t_2). At this time, the normal voltage across the capacitance would have had its crest value, but, because the capacitance has been discharged by the short circuit, the actual voltage is zero. As soon as the short circuit is disconnected by the breaker, voltage e_C rises rapidly. Because of the inductance, the voltage overshoots and would reach twice normal crest value if it were not for the damping effect of the resistance. The voltage then approaches the normal curve through a damped oscillation, the frequency of which is $f_r = \frac{1}{2\pi\sqrt{LC}}\cdot$ In this circuit, the recovery voltage e_r across the open contacts of the circuit breaker is equal to e_C. The rate of rise of recovery voltage is greater the higher is the natural frequency of the circuit, hence the lower are L and C.

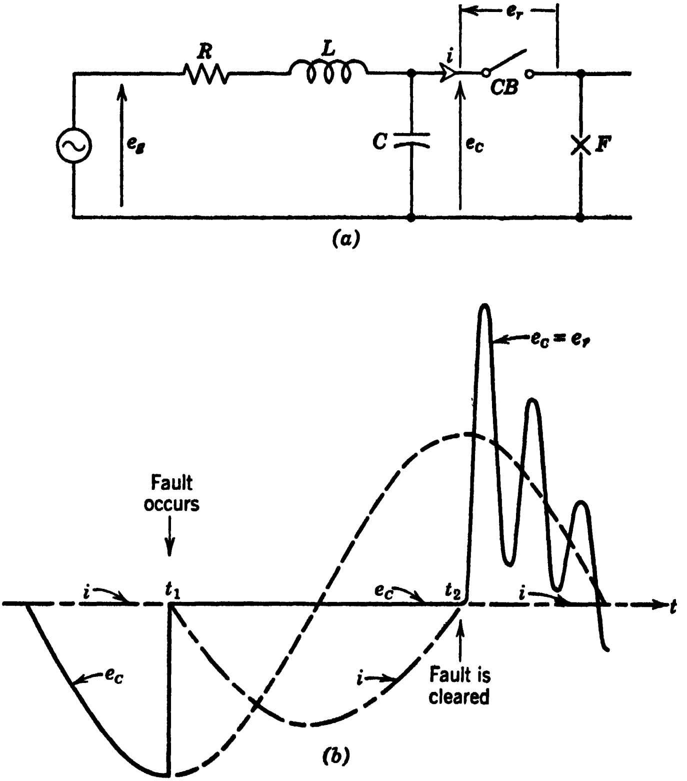


Fig. 10. Simple single-phase circuit for illustrating recovery voltage.

In recent years much study has been given to system recovery voltages and to methods of computing them.[C] Although conditions in a three-phase power system are considerably more complicated than in the simple circuit of Fig. 10, it is still found that the most severe condition with respect to recovery voltage occurs if the breaker is connected to a lumped inductance, such as that of a reactor or transformer, through conductors of small distributed capacitance. Under this condition the natural frequency is high, giving a high rate of rise of voltage after a short circuit has been interrupted. As a rule, the circuit-breaker locations where the fault current to be interrupted is greatest have a relatively low natural frequency and, consequently, a low rate of rise of recovery voltage because the transmission lines which supply the fault current have considerable capacitance. But, when a circuit breaker is tested in a laboratory, the natural frequency and the rate of rise of recovery voltage are greater than in a field test on a power system.

In the foregoing discussion of recovery voltage, it was assumed that after the circuit had been opened it remained open. If, however, the dielectric strength of the arc path in the breaker does not increase fast enough, the arc may be restruck one or more times. If these restrikes occur very soon after the initial interruption of current, they do no harm, and the interruption phenomenon is merely repeated at the next current zero. If, however, a restrike occurs after a current pause of one-fourth cycle or more, as is likely to happen when the charging current of line capacitance is being interrupted, considerably greater transient overvoltages may be produced than if there were no restriking.

The production of overvoltages by delayed restrikes will be explained with reference to the simple circuit of Fig. 11, in which C represents the capacitance of an unfaulted transmission line. When breaker CB is opened, the charging current i is easily interrupted at a normal current zero soon after the contacts part because the current is low and the rate of rise of recovery voltage is also low. The opening of the circuit leaves a charge trapped on the capacitance, and voltage e_C across the capacitance remains at the value it had when the circuit was opened, which is the crest value of the normal voltage e_g, which lagged 90° behind the charging current i. The voltage e_r across the open breaker, which is the difference of e_s and e_C, is initially zero and increases slowly at first, but, half a cycle later, when e_g and e_s have reversed, reaches twice normal crest value. Suppose that at this instant the insulation between contacts (oil or air) breaks down and the arc is restruck. If the initial interruption occurred when the contacts had separated only a short distance, it is likely that half a cycle later the contact separation would still be small enough to make a restrike possible. Now that the circuit is reclosed, a high-frequency oscillation of e_C occurs around the normal voltage e_g, which now has its negative crest value; that is, e_C oscillates between $+1$ and -3 times this crest value (resistance being neglected). Meanwhile e_r is zero. Now suppose that at the first zero of the high-frequency current, when e_C is -3 times the normal crest value, the arc is again extinguished, with the result that e_C remains constant at its new value. If a second restrike occurs half a cycle (of normal frequency) later, the high-frequency oscillation could bring e_C up to $+5$ times normal crest value.

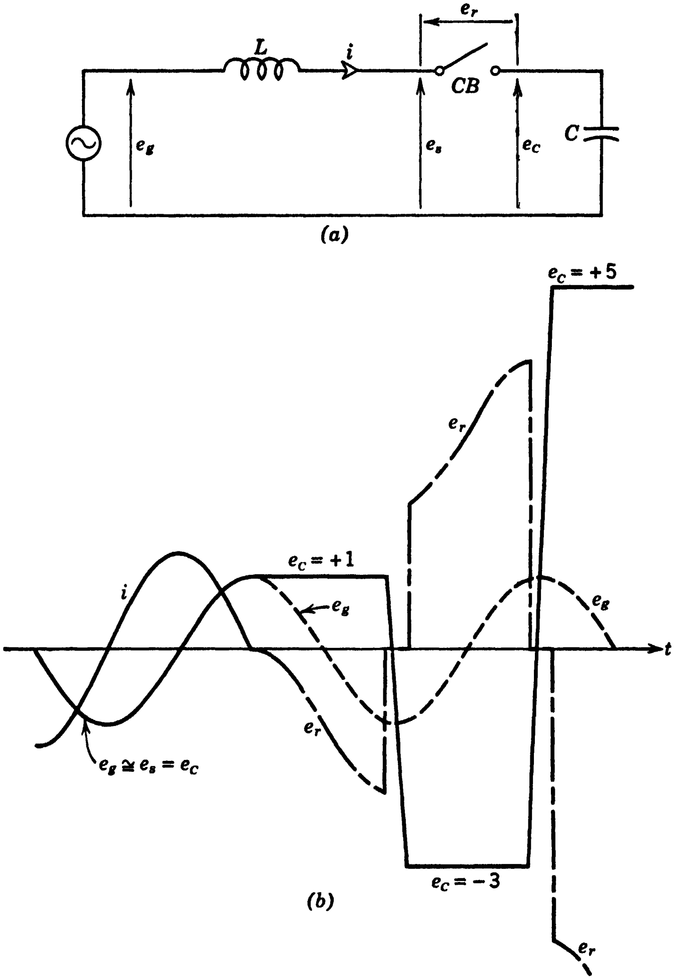


FIG. 11. Switching transient in which the arc in the circuit breaker is restruck during the interruption of charging current.

Restrikes have been assumed to occur at the instants which would result in the production of the greatest transient voltages. For restrikes to occur at such instants, the strength of the dielectric between the contacts would have to increase at a certain rate. If it increased faster, there would be no restrikes; and, if it increased much slower, restrikes would occur at a much lower voltage so that the transient voltages would be much lower.

Having briefly discussed the problem of extinguishing an a-c. arc caused by the interruption of either short-circuit or charging current, we now turn to a consideration of some devices used in practical oil circuit breakers for helping to extinguish such arcs.

Devices to aid arc extinction in oil. Small oil circuit breakers are usually of the plain-break type, having two breaks in series per pole and no special attachments for assisting in the extinction of the arc. In large oil circuit breakers, additional means must be used to obtain the required interrupting capacities and speeds. A common and effective method is to confine the arcs to suitable chambers, attached to the stationary contacts of the breaker, within which chambers pressure is produced by the volatilization of the oil by the heat of the arc. The pressure forces a blast of gas or oil out through openings in the chambers which are so located as to direct the blast through the arc path. Among the devices of this kind offered by different manufacturers are "explosion chambers," "oil-blast chambers," "expulsion chambers,"[D29] "Ruptors,"[D38] "dethermalizing arc quenchers,"[D49] "De-ion grids," and "multi-flow De-ion grid interrupters." Devices of this category are called *interrupters of the self-generated pressure type*. Some of the most widely used of them are described below. In other circuit breakers, the stream of oil through the arc path is produced wholly or partially by pistons. Other means of aiding arc extinction, used either alone or in conjunction with one of the devices just mentioned, are the employment of more than two breaks in series per pole and the use of shunt resistors.

Explosion chamber. One of the earliest devices for aiding arc extinction in oil was the explosion chamber, shown in Fig. 12. The arc formed in the chamber volatilizes some oil and generates pressure which, acting on the piston-like contact rod, helps the operating mechanism to part the contacts rapidly. As soon as the mouth of the chamber is opened by the passage of the end of the contact rod through it, oil and gas are forced out the mouth and, therefore, through the arc which has been drawn through the mouth. Explosion chambers have been superseded by oil-blast devices.

Oil-blast breakers|| break the circuit successively at two different sets of contacts in series. The arc formed by the parting of the first set of contacts volatilizes some of the oil, forming a bubble of gas. The

---

||References D8, 11, 12, 14, 17, 18, 21, 24, and 32.

expansion of this gas bubble in a properly designed baffle chamber forces a stream of oil into or across the arc formed by the parting of the second set of contacts. The flow of fresh oil cools the arc, and, after a current zero, it interposes a barrier of high dielectric strength across the arc path to prevent restriking of the arc.

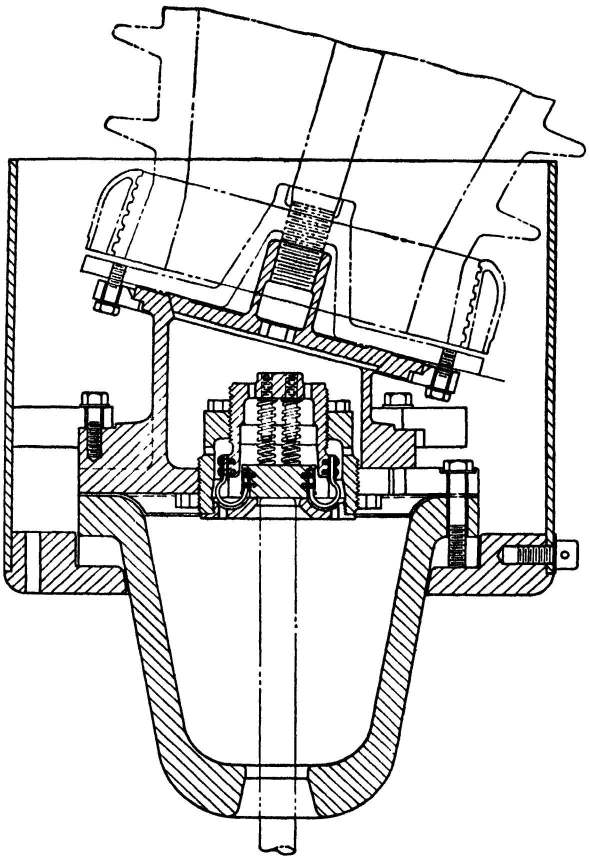


FIG. 12. Explosion chamber—an early device for aiding arc extinction in oil circuit breakers, now obsolete. The chamber, made of insulating material, is attached to the lower end of the bushing. The movable contact rod enters the chamber through the hole at the bottom and engages the butt-type stationary contact at the top of the chamber. (By courtesy of the General Electric Company)

The oil-blast principle is applied in several different forms, as illustrated in Figs. 13 to 16. Figure 13 shows a small circuit breaker in which a *horizontal baffle plate* is attached to the studs just above the stationary contacts, dividing the tank into two parts connected only through small passages on each side. The left-hand contacts open first, and the arc there sets the oil in motion. When the right-hand contacts open, oil is sweeping through the arc, as shown in the figure.

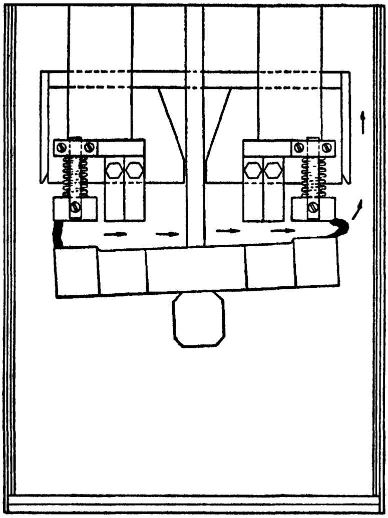
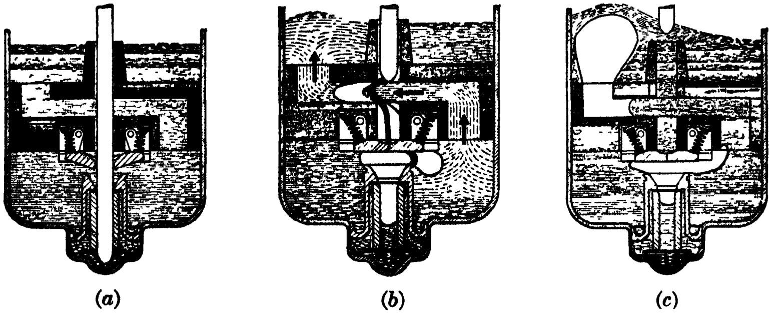


FIG. 13. Section through rectangular-tank-type oil-blast circuit breaker with horizontal baffle and side walls, showing the flow of oil due to unbalanced pressures. (By courtesy of the General Electric Company)



(a) (b) (c)

FIG. 14. Cross oil-blast baffle, as used in low-oil-content, live-tank, station breakers similar to that shown in Fig. 7. (a) Breaker closed. (b) Breaker opening. (c) Arc interrupted. (By courtesy of the General Electric Company)

Figure 14 shows a *crossjet baffle* used in a live-tank station-type circuit breaker. As the contact rod moves upward to open the circuit, it draws an arc in the lower compartment, followed by a second arc between the gates and the rod. The pressure developed by the lower arc forces oil through the passageway crossing the upper arc path.

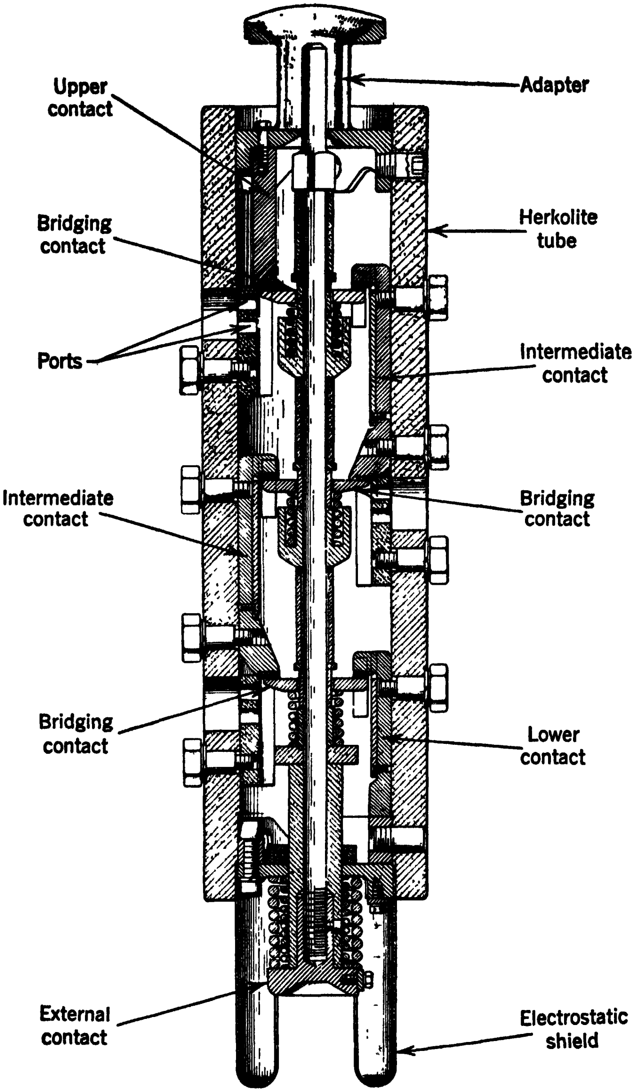


FIG. 15. Multibreak oil-blast interrupter for 191–239-kv. tank-type 5-cycle oil circuit breaker. There are six breaks in series in each interrupter or twelve per pole. For 115–161 kv., eight breaks per pole are used. (From Ref. D56 by permission of the A.I.E.E. and by courtesy of the General Electric Company)

Figure 15 shows a *multibreak oil-blast interrupter*, having six breaks in series per interrupter, or twelve per pole. In each interrupter there are three moving bridges connected to the central operating rod. The contact assembly is enclosed in an insulating cylinder which supports the stationary contacts and forms the oil-blast chamber. Ports in one side of the cylinder opposite each pair of contacts furnish passages for the oil blast.

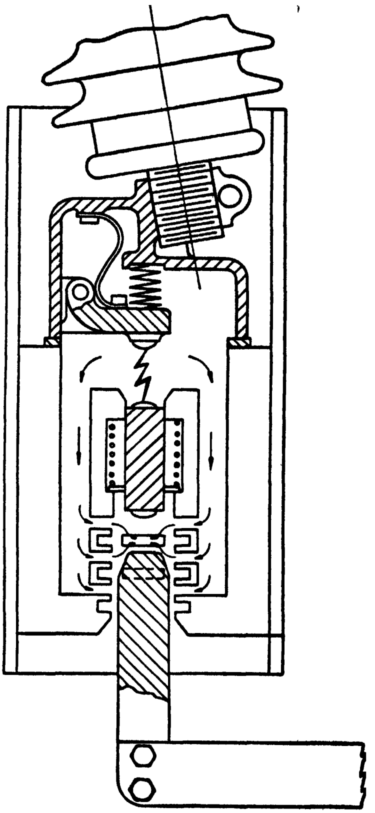


FIG. 16. Multi-flow De-ion grid interrupter for 138-kv., 5-cycle oil circuit breaker. (From Ref. D50 by permission of the A.I.E.E. and by courtesy of Westinghouse Electric Corporation)

Figure 16 shows a *multi-flow De-ion¶ grid* interrupter[D48, 50, 52, 55] having an upper and a lower chamber connected by vertical passages. The lower chamber and passages consist of a stack of punched fiber plates. An intermediate contact slides in a hole in the baffle between the two chambers. When the lower contact, attached to the crosshead, moves downward to open the circuit, the intermediate contact follows it at first, being forced downward by a spring, and a pressure-generating arc is drawn between the upper and intermediate contacts in the upper chamber. Later, when the intermediate contact reaches the limit of its travel, the main arc is drawn between the intermediate and lower contacts in the lower chamber. Pressure generated in the upper arc forces oil down the vertical passages, through the lower arc at several different levels, and out through holes in the wall of the lower chamber. The number of inlet and outlet levels varies with the voltage rating. A check valve at the top of the upper chamber remains closed during current interruption but opens at other times to allow escape of gas and circulation of oil.

*Impulse circuit breaker.*** The impulse circuit breaker is similar in principle to the oil-blast circuit breaker except that the pressure which causes the oil stream is produced by a piston driven by the operating mechanism of the circuit breaker. (See Fig. 17.) As a result, both the volume of flow of oil and its timing are independent of the magnitude of the current interrupted. By proper design of the impulse circuit breaker, the oil flow may be made greater for a given current than it is in the oil-blast breaker, and the interrupting time may be correspondingly reduced. The 287.5-kv., 2,500-Mva. circuit breakers installed at the desert switching stations in the Boulder Dam–Los Angeles transmission line are of the low-oil-content porcelain-clad impulse type with eight breaks per pole, and they have a rated interrupting time of 3 cycles.[D31] A later model of impulse-type circuit breaker, in which the interrupting rating was increased to 10,000 Mva., is shown in Fig. 18. Such a breaker was installed at Grand Coulee Dam in 1949.

¶"De-ion" is a trade name of the Westinghouse Electric Corporation and is applied to several different types of circuit breakers made by that company.

**References D13, 26, 30, 31, 37, and 41.

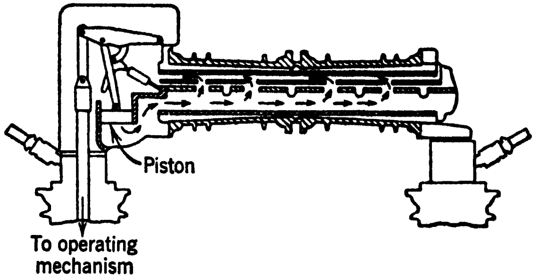


FIG. 17. Impulse oil circuit breaker with four breaks in series. Arrows show flow of oil from piston, across arc path, and through ports opposite each contact, when breaker is tripped. (By courtesy of the General Electric Company)

Circuit breakers with auxiliary pistons.[D50, 55] Some oil circuit breakers in which the flow of oil through the arc is caused principally by pressure generated by the arc itself have pistons driven by the operating mechanism through springs. While the circuit breaker is interrupting short-circuit current, the pressure generated by the arc overcomes the force of the spring and keeps the piston from moving immediately. After the pressure has dropped, however, the piston pushes clean oil through the interrupter to flush out the contaminated oil. When the circuit breaker is interrupting small current, such as line-charging current, the self-generated pressure is not great enough to provide much flow of oil through the arc or to hold back the piston. In this event, the piston moves immediately and provides a flow of oil, preventing restrikes which otherwise might occur. An interrupter with auxiliary piston is illustrated in Fig. 19.

De-ion magnetic grid breakers[D6] differ in principle from oil-blast breakers in that the arc is moved through the oil by magnetic force instead of, or in addition to, the oil being moved through the arc. In breakers of this type the arc is drawn by the moving contact through a deep narrow groove in a stack of slotted plates, the "De-ion grid," attached to the lower end of each bushing. (See Figs. 20 to 22.) Most of the plates in the stack are of insulating material, but some of them are of iron. The iron plates form a partial magnetic circuit for

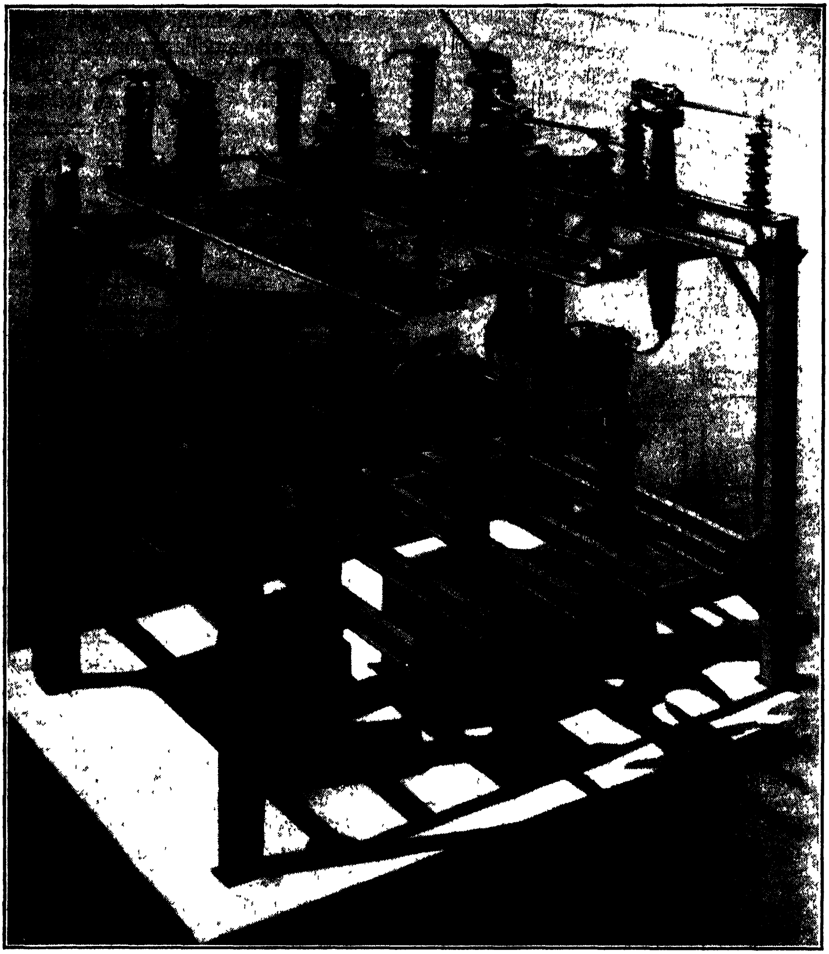


FIG. 18. Outdoor switching station with high-speed, impulse-type, oil-blast circuit breaker rated 230 kv., 1,000 amp., 3 cycles, 10,000 Mva. (By courtesy of the General Electric Company)

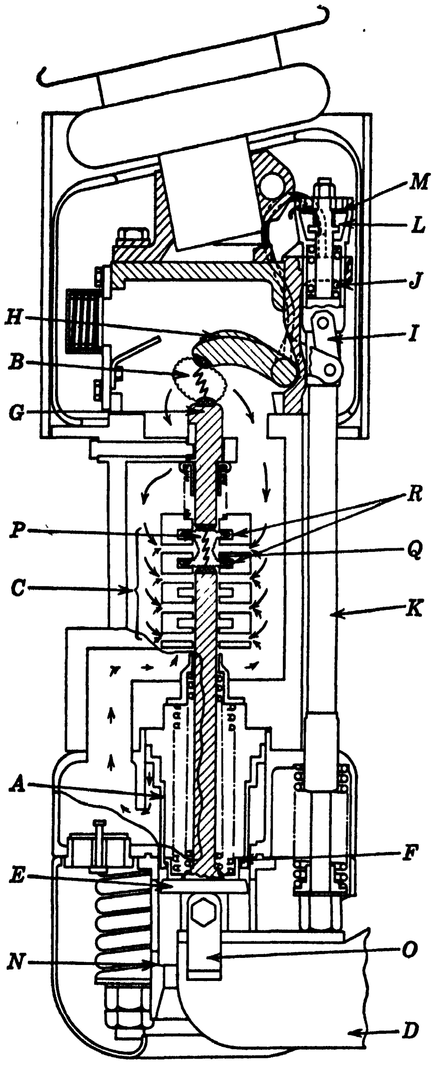


Fig. 19. Cross section of 230-kv., 10,000-Mva. multi-flow grid interrupter with auxiliary piston. When the circuit breaker is tripped, crossarm *D* moves downward, followed by lower contact *E* and by operating rod *K*. Rod *K*, acting through links *I*, rotates rocker contact *H* upward. Intermediate contact *G* is spring-biased upward and follows rocker contact *H* for a short distance. Thus the main arc is struck at *P* and is rapidly lengthened by the simultaneous downward motion of lower contact *E* and upward motion of intermediate contact *G*. A little later, the pressure-generating arc is formed at *B* and causes oil to flow (as indicated by heavy arrows) to interrupting section *C*, through orifice plates *Q*, through arc *P*, and out through vents *R* at both front and back. After a short delay to provide time for adequate contact separation at *P* for interruption of charging current without restriking, collar *F*, following lower contact *E*, picks up piston *A*. Oil flow from piston *A*, indicated by light arrows, augments the flow of oil from arc *B*. Finally, after the arc has been extinguished in the interrupter, lower contact *E* is stopped on shoulder *N*, allowing crossarm *D* to pull out of fingers *O* to form an isolating gap. When the circuit breaker is closed, spring *J* is compressed to load contact *H*, but, during opening, extension of the spring is opposed by an oil dashpot *L* in order to speed the opening of the contact. During closing, the dashpot is freed by opening of check valve *M*. (From Ref. D60 by permission)

the flux set up by the arc current, the circuit being completed by passage of the flux across the slot. The interaction of the arc current and the flux in the slot forces the arc through the oil toward the closed end of the slot. The gas formed by volatilization of oil can escape from the groove only at the open side, top, and bottom; and thus much of the gas is forced through the arc, helping to deionize it.

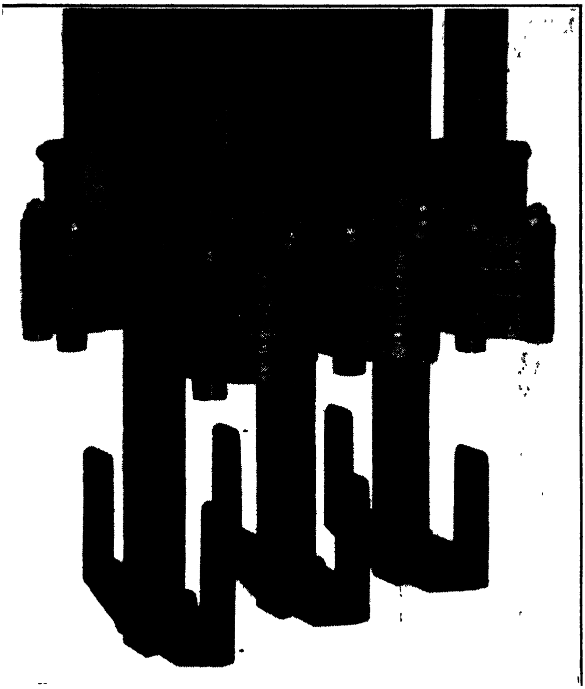


FIG. 20. De-ion grids in a common-tank breaker. (By courtesy of the Westinghouse Electric Corporation)

Multibreak circuit breakers. By the use of a larger number of breaks in series per pole, it is possible to increase the aggregate arc length at a more rapid rate than would be feasible with only two breaks per pole. Furthermore, even on the basis of equal rates of increase of total arc length, an increase in the number of arcs in series is advantageous, possibly because of the cooling effect of the added electrodes. The multibreak principle is used either alone or in combination with the oil-blast, gas-blast, or impulse principles or with De-ion grids. A multibreak oil-blast interrupter is shown in Fig. 15, and a multibreak impulse interrupter, in Fig. 17. A six-break oil circuit breaker with "expulsion chambers"[D29] on all the stationary contacts is shown in Fig. 23. The moving contacts of this breaker are given rotary motion in horizontal planes by the vertical Bakelite cylinder. The 287-kv., 3-cycle oil circuit breakers at the Boulder Dam end of the lines to Los Angeles have ten breaks per pole, each equipped with a De-ion grid.[D36]

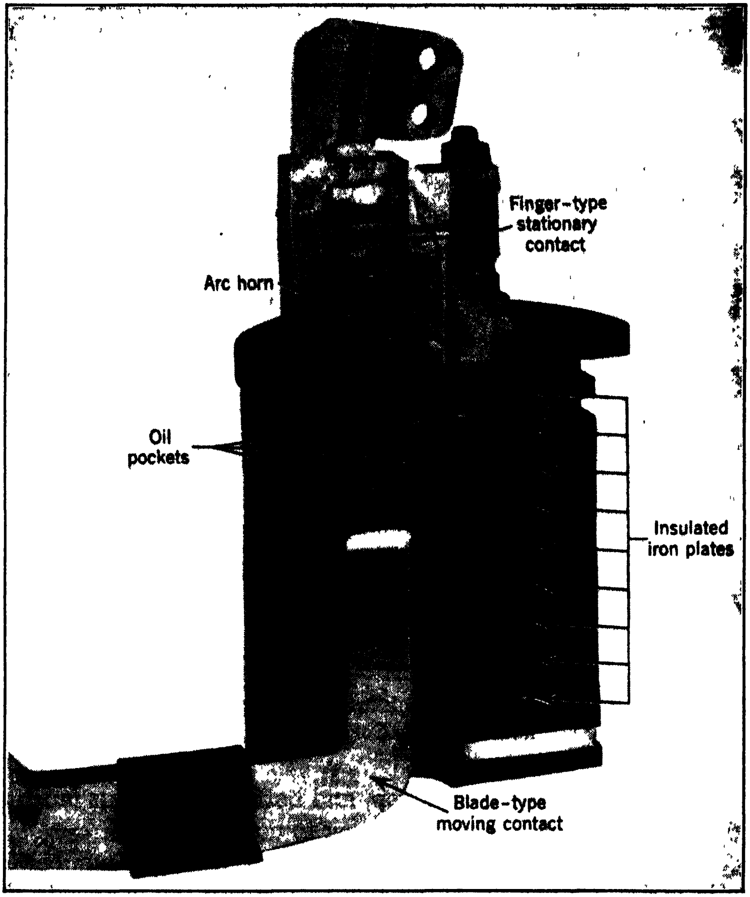


FIG. 21. Sectioned De-ion grid with finger-type contact. (By courtesy of Westinghouse Electric Corporation)

Multiple breaks are most effective if the recovery voltage divides equally across the several breaks. The division of voltage can be controlled by shunt resistances or capacitances.

Resistors shunting the contacts of circuit breakers have been used for several purposes. In a multibreak circuit breaker, as was mentioned above, shunt resistors can make the recovery voltage divide equally among the several breaks in series. Resistors for this purpose are of several hundred thousand ohms.

Somewhat lower resistances (a few thousand ohms) are used to reduce the transient overvoltages that occur during interruption of line-charging current.[C21] The resistor provides a connection across the circuit-breaker contacts which allows the capacitance voltage to follow the changing generator voltage after arc extinction, even though with a considerable phase lag. The available restriking voltage is reduced, therefore, and, even if a delayed restrike does occur, the crest value that the capacitance voltage can reach during a high-frequency oscillation will be much less than if there were no resistor.

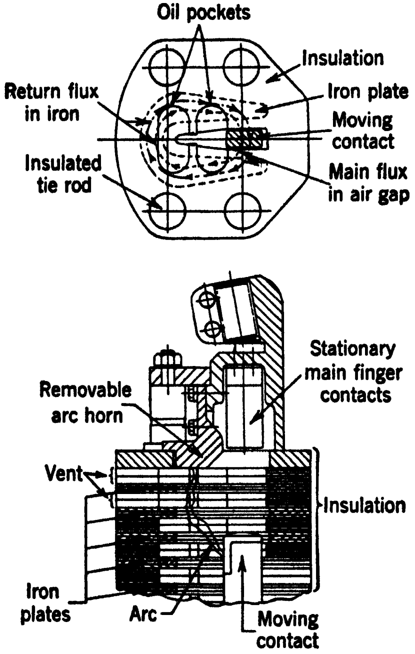


FIG. 22. De-ion grid. (By courtesy of Westinghouse Electric Corporation)

Resistors of several thousand ohms or less are useful in both oil and air circuit breakers for damping the recovery-voltage transients that occur during the interruption of fault currents.

The small current through the high resistance shunting the contacts must be broken by additional series contacts. To be most effective in decreasing transient recovery voltage, the resistance must be so low that interruption of the resistor current presents a problem, and, therefore, resistors are seldom used for that purpose. The use of two resistance steps has been advocated for air-blast circuit breakers in order to make their interrupting capacity and time independent of circuit recovery voltage.[G42]

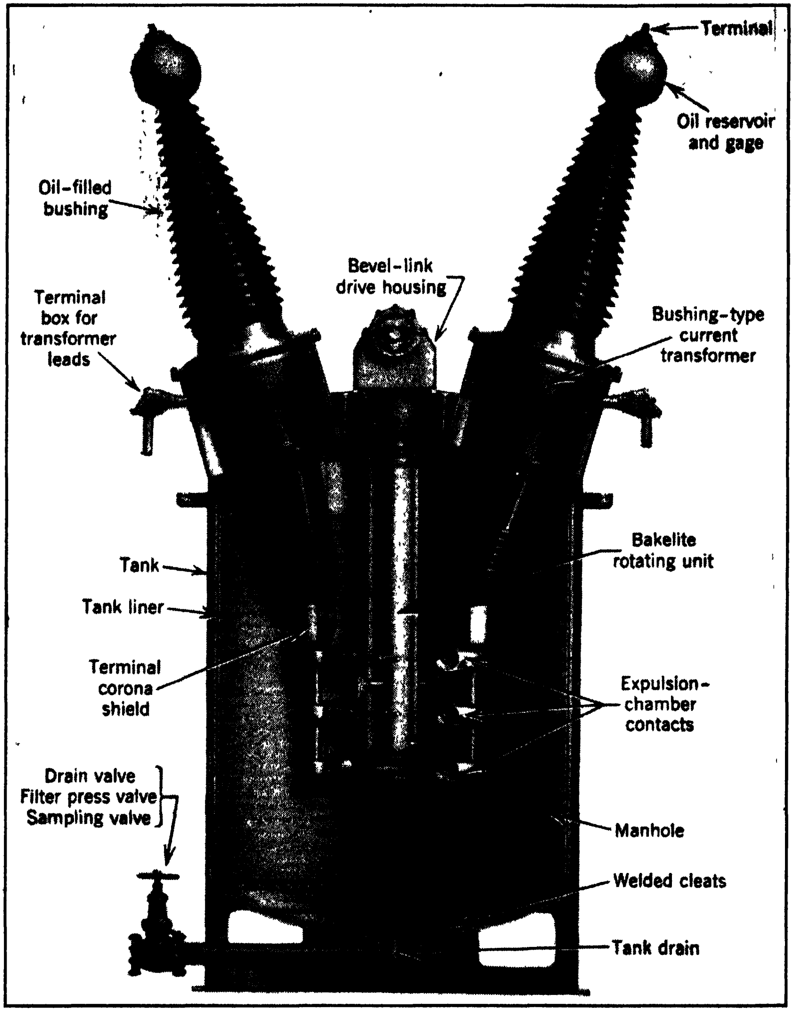


FIG. 23. Rotary six-break circuit breaker with expulsion chambers. (By courtesy of Pacific Electric Manufacturing Corporation)

Closing of the circuit through resistance has been used to decrease the magnetizing inrush current of transformers.

Modernization of oil circuit breakers.$^{E1-6}$ Many of the older oil circuit breakers having interrupting times of 15 to 30 cycles can be rebuilt to reduce the time to that of modern breakers, 8 or even 5 cycles, and at the same time to increase the interrupting capacity, sometimes as much as to four or five times the original value. Modernization is accomplished by installing new contact assemblies (for example, oil-blast chambers or De-ion grids) and by replacing the operating mechanism with a new high-speed mechanism.

Maintenance of oil circuit breakers. The chief maintenance work required on oil circuit breakers is replacement of contacts and of oil. When a breaker interrupts short-circuit current, the contacts may be worn by arcing. In addition, the oil becomes carbonized in the vicinity of the contacts, thereby losing some of its dielectric strength. The dielectric strength of the oil and the interrupting capacity of the breaker are restored partially as the contaminated oil is diffused through the rest of the oil. After a breaker has interrupted fault current a few times, or load current many times, the oil becomes deteriorated to such an extent that it needs to be replaced. Used oil may be purified with a blotter filter press, a centrifuge, or both, to remove carbon particles, water, and sludge. The dielectric strength of the oil should be checked periodically by testing samples drawn from the bottoms of the tanks.

Less maintenance is required on modern or modernized high-speed breakers than on old low-speed breakers.

Air power circuit breakers. Although oil circuit breakers were for many years the only type with high interrupting capacity, and although they have been greatly improved in recent years, they have important disadvantages, which have given impetus to the development of various oilless and "oil-poor"$^{D34, 47}$ circuit breakers of sufficient capacity. The principal disadvantage of oil circuit breakers is the fire hazard, due to the inflammability of the oil and of the gas formed by the decomposition of the oil.^{D23} Rupture of currents beyond the capacity of the breaker or sticking of the operating mechanisms leads occasionally to prolonged arcing and consequent production of abnormally large amounts of gas, high pressures, and high temperatures, and, once in a while, to the bursting of tanks, throwing of oil, and emission of flame. The fire hazard is considerably greater with indoor than with outdoor oil circuit breakers, because outdoor switchgear usually has plenty of space around it. The combustion of a little oil can form much soot, which, collecting on the surface of insulators of indoor switchgear, can cause an extended shutdown. A second disadvantage of oil circuit breakers is the necessity of facilities for handling, storing, testing, and reclaiming the oil, and for lowering and lifting heavy oil-filled tanks.

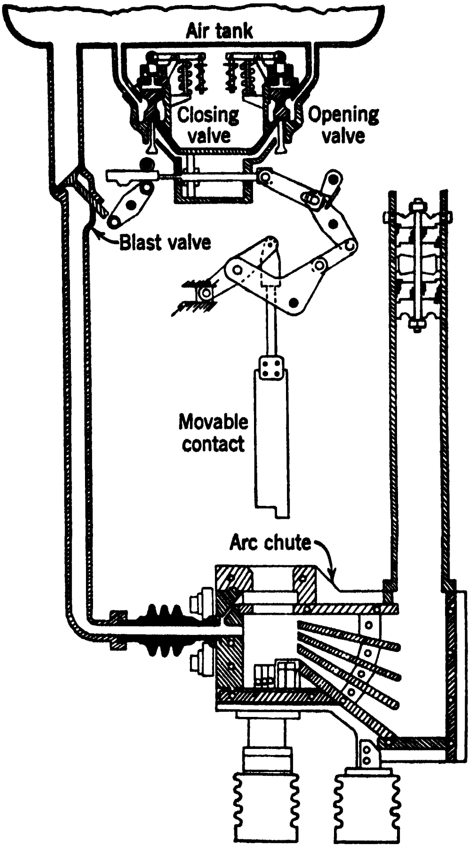


FIG. 24. Schematic diagram showing operation and principal parts of cross-blast air circuit breaker. (By courtesy of the General Electric Company)

Indoor air circuit breakers are now available in ratings (Table 3, p. 41) paralleling those of indoor oil circuit breakers (Table 1, p. 39). Ratings up to 500 Mva. at 13.8 kv. are of the magnetic-blowout type (for example, the De-ion air circuit breaker[F1-6, 8-10, 12] of the Westinghouse Electric Corporation and the Magne-blast circuit breaker[F7, 11, 13] of the General Electric Company). Larger ratings up to 2,500 Mva. at 14.4 kv. and 34.5 kv. are of the air-blast type. Outdoor high-voltage air-blast circuit breakers are common in Europe but not yet in the United States.

Air-blast circuit breakers were developed in Germany by S. Ruppel and J. Biermanns[G1] and were extensively employed in Europe before they came into use in the United States. In air-blast breakers the arc is extinguished by a stream of air blown through it as the contacts separate. There are two principal types, the cross blast and the axial blast. The cross blast is now commonly used in indoor circuit breakers of the medium-high-voltage class, whereas the axial blast is used in high-voltage breakers. In both types, compressed air is used also to open and close the contacts.

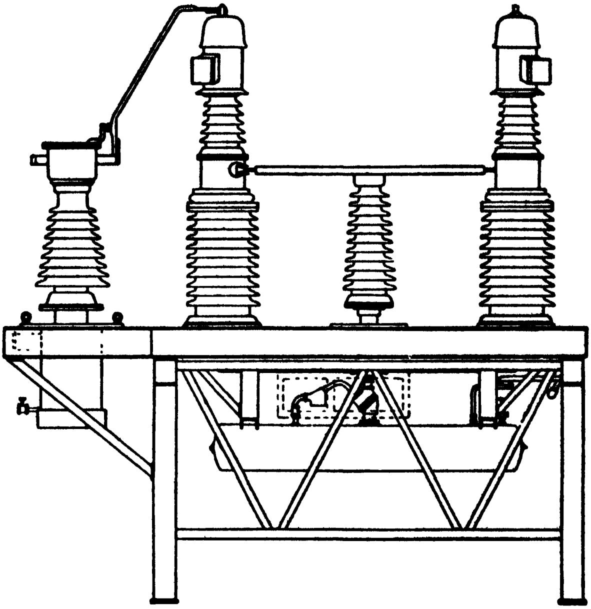


FIG. 25. Outline of single-pole unit of 138-kv. outdoor axial-air-blast circuit breaker. (By courtesy of the General Electric Company)

A cross-blast air circuit breaker is shown in Fig. 24. The movable contact is raised by a piston when air is admitted from the tank through the opening valve to one end of the operating cylinder and is lowered when air is admitted through the closing valve to the other end of the cylinder. The blast valve is mechanically connected to the operating mechanism so that the air blast is always provided as the contacts open. The arc is blown into an arc chamber consisting of several wedge-shaped sections separated by fiber splitter plates.

An axial-air-blast circuit breaker for high-voltage outdoor service[G3] is illustrated in Figs. 25 and 26. The high voltage and consequent low current make this type preferable to the cross-blast breaker. There are two porcelain-clad air-blast interrupters in series per pole, each supported on a pillar insulator, and a rotary air-break switch between the two interrupters. When compressed air is supplied through the blast valve to the interrupters (Fig. 26), the piston raises the movable butt contact, drawing an arc in the throat. At the same time, exhaust ports are opened which permit a stream of air to pass through the arc and to extinguish it. In an opening operation of the breaker, the interrupters first break the current; then, while the interrupter contacts are still open, the air-break isolating switches open under no load; and, finally, the interrupter contacts reclose. A closing operation is performed by means of the air-break switches alone, the interrupter contacts remaining closed. In high-speed reclosing operations, the interrupter contacts open and reclose while the air-break switches remain closed.

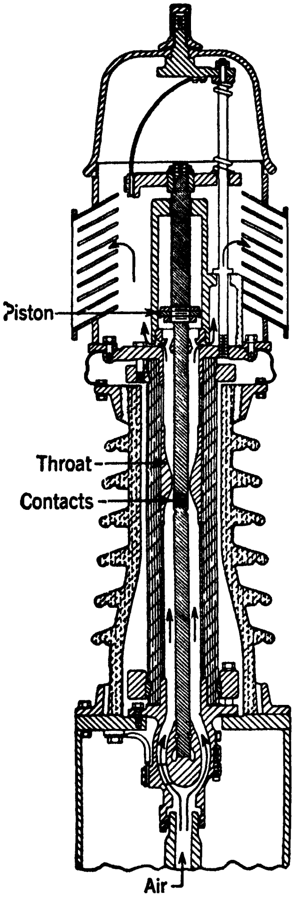


Fig. 26. Section of interrupting unit of 138-kv. outdoor axial-air-blast circuit breaker. Arrows show path of air flow when breaker opens. (By courtesy of the General Electric Company)

An outdoor, 220-kv., 2,500-Mva., air-blast reclosing circuit breaker, manufactured in Germany about 1939, is shown in Fig. 27.[G39] Each of the three poles consists of two vertical porcelain columns about 10 ft. high and 9 ft. apart, mounted directly above a compressed-air tank which forms an integral part of the frame. Each column has a horizontal disconnecting arm attached to its top and meeting a similar arm attached to the top of the other column of the same phase. The air-break switch formed by the two arms is opened by rotation of both columns about their axes. At the end of each disconnect arm and perpendicular to it is an air-blast interrupter. The interrupter, which is shown in more detail in Fig. 28, has a retractable contact mounted in a porcelain-clad extinguishing head. The contacts are hollow round copper rods of 1¼-in. outside diameter.

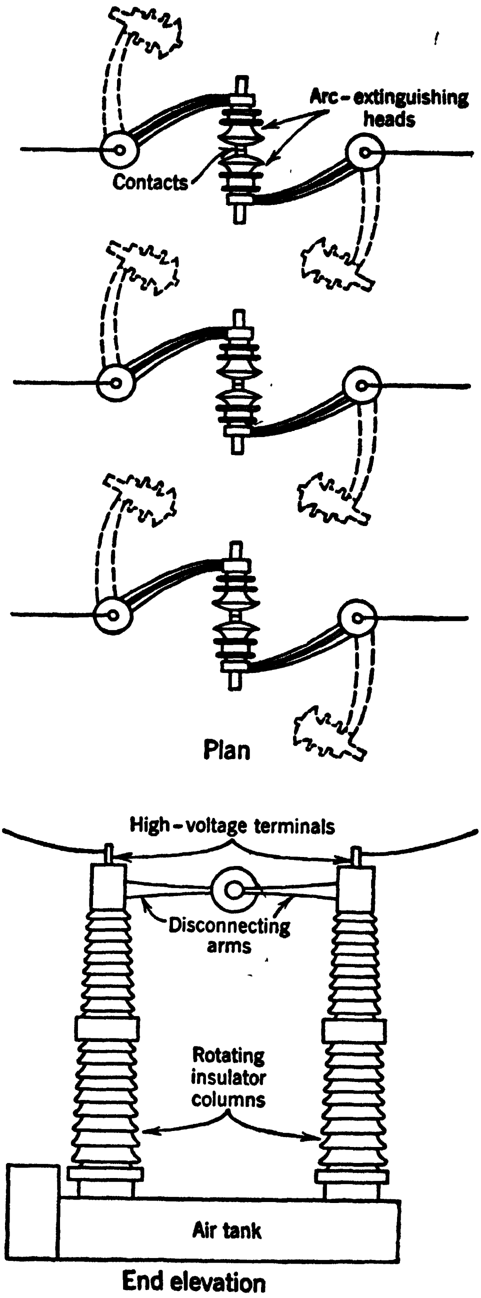


FIG. 27. A.E.G. free-jet air-blast 220-kv., 2,500-Mva. circuit breaker.[G39]

In the closed position, the contacts mounted on two opposite arms protrude from the extinguishing heads into the open air and are butted together by spring pressure. When the blast valve is opened, compressed air forces the contacts to withdraw into a hard rubber sheath and at the same time sends jets of air through the arc from each interrupter head into the open air. For this reason, the breaker is called a "free-jet" type.

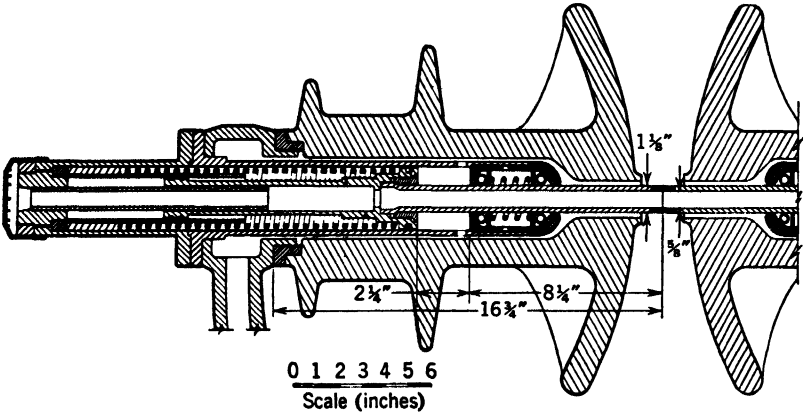


FIG. 28. Section of interrupter head of A.E.G. free-jet air-blast 220-kv. circuit breaker. (From Ref. G39 by permission)

In a full opening operation, action of the air-blast interrupters is followed by rotation of the columns and disconnecting arms. Closing is accomplished by rotation with no air blast. Opening followed by rapid reclosing is performed by the air-blast interrupters alone. Either three-pole or single-pole operation can be effected.

One of these circuit breakers was tested in February, 1947, by the Bonneville Power Administration. It was found to interrupt 60-cycle short-circuit currents up to its interrupting rating satisfactorily in 6 cycles or less, but during interruption of line-charging currents restriking continued even after rotation of the columns had commenced.

Ratings of power circuit breakers. To clear faults successfully without excessive damage to the circuit breakers, breakers of proper rating must be used. Hence a discussion of circuit-breaker ratings is pertinent.

The methods of rating circuit breakers in the United States are prescribed by the American Standards Association.[K6] Circuit breakers are given ratings as to normal voltage, maximum voltage, low-frequency and impulse withstand voltage, frequency, continuous current, short-time current (momentary and 4-sec.), interrupting current at rated voltage, maximum interrupting current, interrupting kilovolt-amperes, interrupting time, making current, and latching current. These items of rating will be discussed one by one together with some closely related matters. The ratings of circuit breakers manufactured in the United States usually conform to the schedule of preferred ratings recommended by the A.S.A.[K8] (see Tables 1, 2, and 3).

TABLE 1

Preferred Ratings for Power Circuit Breakers

Indoor Oil Power Circuit Breakers

(Condensed from Ref. K8)

Line	Rated Voltage (kv.)	Current Ratings		Interrupting Ratings		
		Continuous 60 c.p.s.* (ka.)	Short-Time Momentary† (ka.)	3-phase Mva.	Current at Rated Voltage (ka.)	Maximum Current† (ka.)
1	4.16	1.2	20	50	7	12.5
2	7.2	0.6	20	50	4	12.5
3	7.2	0.6	40	100	8	25
4	7.2	1.2	40	100	8	25
5	7.2	2.0	40	100	8	25
6	13.8	0.6	35	150	6.3	22
7	13.8	1.2	35	150	6.3	22
8	13.8	1.2	60	250	10.6	36
9	13.8	1.2	70	500	21	44
10	13.8	2.0	70	500	21	44
11	14.4	1.2	70	500	20	44
12	14.4	1.2	77	1,000	40	48
13	14.4	3.0	77	1,000	40	48
14	14.4	2.0	115	1,500	60	72
15	14.4	4.0	115	1,500	60	72
16	34.5	1.2	61	1,500	25	38
17	34.5	3.0	61	1,500	25	38

All breakers listed have a rated interrupting time of not more than 8 cycles (0.13 sec.) and are rated on the CO–15 sec.–CO duty cycle.

*For 25-c.p.s. ratings see Table 4.

†The rated short-time 4-sec. current is equal to the rated maximum interrupting current.

TABLE 2

PREFERRED RATINGS FOR POWER CIRCUIT BREAKERS
OUTDOOR OIL POWER CIRCUIT BREAKERS

(Condensed from Ref. K8)

Line	Rated Voltage (kv.)	Current Ratings		Interrupting Ratings			
		Continuous 60 c.p.s.* (ka.)	Short-Time Momentary† (ka.)	3-phase Mva.	Current at Rated Voltage (ka.)	Maximum Current† (ka.)	Time (cycles)
1	7.2	0.6	20	50	4	12.5	8
2	14.4	0.6	24	100	4	15	8
3	14.4	0.6	40	250	10	25	8
4	14.4	1.2	40	250	10	25	8
5	14.4	1.2	77	1,000	40	48	8
6	14.4	3.0	77	1,000	40	48	8
7	14.4	2.0	115	1,500	60	72	8
8	14.4	4.0	115	1,500	60	72	8
9	23	0.6	19	250	6.3	12	8
10	23	1.2	38	500	12.6	24	8
11	34.5	0.6	20	500	8.4	12.6	8
12	34.5	1.2	40	1,000	17	25	8
13	34.5	1.2	61	1,500	25	38	8
14	34.5	2.0	96	2,500	42	60	8
15	46	0.6	12	500	6.3	7.2	8
16	46	1.2	35	1,500	19	22	8
17	69	0.6	16	1,000	8.4	9.6	8
18	69	1.2	23	1,500	12.6	14.5	8
19	69	1.2	38	2,500	21	24	8
20	69	2.0	53	3,500	29	33	8
21	115	0.8	13.5	1,500	7.5	8.3	5
22	115	1.2	31	3,500	17.5	19.3	5
23	138	0.8	11.5	1,500	6.3	7.2	5
24	138	1.2	27	3,500	14.7	17	5
25	138	1.2	38.5	5,000	21	24	3
26	161	1.2	21.5	3,500	12.5	13.5	5
27	161	1.2	31	5,000	18	19.3	3
28	230	0.8	15	3,500	8.8	9.2	3
29	230	0.8	21	5,000	12.5	13	3

All breakers listed are rated on the CO–15 sec.–CO duty cycle.

*For 25-c.p.s. ratings see Table 4.

†The rated short-time 4-sec. current is equal to the rated maximum interrupting current.

TABLE 3

Preferred Ratings for Power Circuit Breakers
Indoor Oilless Power Circuit Breakers
(Condensed from Ref. K8)

Line	Rated Voltage (kv.)	Current Ratings		Interrupting Ratings‡		
		Continuous 60 c.p.s.* (ka.)	Short-Time Momentary† (ka.)	3-phase Mva.	Current at Rated Voltage (ka.)	Maximum Current† (ka.)
1	4.16	0.6	20	50	7	12.5
2	4.16	1.2	20	50	7	12.5
3	4.16	0.6	40	150	21	25
4	4.16	1.2	40	150	21	25
5	4.16	2.0	40	150	21	25
6	4.16	1.2	60	250	35	37.5
7	4.16	2.0	60	250	35	37.5
8	7.2	1.2	51	250	20	32
9	7.2	2.0	51	250	20	32
10	7.2	1.2	70	500	40	44
11	7.2	2.0	70	500	40	44
12	13.8	0.6	20	150	6.3	13
13	13.8	1.2	20	150	6.3	13
14	13.8	1.2	35	250	10.6	22
15	13.8	2.0	35	250	10.6	22
16	13.8	1.2	[illegible]	[illegible]	21	25
17	13.8	2.0	[illegible]	[illegible]	21	25
18	14.4	1.2	[illegible]	1,000	40	48
19	14.4	3.0	77	1,000	40	48
20	14.4	2.0	115	[illegible]	60	72
21	14.4	4.0	115	[illegible]	60	72
22	14.4	5.0	190	2,500	100	120
23	34.5	1.2	61	1,500	25	38
24	34.5	3.0	61	1,500	25	38
25	34.5	3.0	96	2,500	42	60

All breakers listed have a rated interrupting time of 8 cycles (0.13 sec.) and are rated on the CO–15 sec.–CO duty cycle.

*For 25-c.p.s. ratings see Table 4.

†The rated short-time 4-sec. current is equal to the rated maximum interrupting current.

‡These interrupting ratings are for 60-cycle systems.

67,825

Rated normal voltage and maximum voltage are expressed as r.m.s. line-to-line voltages. Rated normal voltage is used in conjunction with interrupting ratings as described below. Rated maximum voltage, which is higher than rated normal voltage by 5% for circuit breakers rated at 46 kv. or over, and by 5 to 10% for lower voltage ratings, should never be exceeded in normal operation. The voltage ratings hold for operation at altitudes not exceeding 3,300 ft. (1,000 meters) above sea level. At higher altitudes breakers must be derated in voltage.

Rated low-frequency and impulse withstand voltages. Although tests on the insulation of circuit breakers to ground, between phases, and across the open contacts both at normal frequency and for impulses are important, a discussion of such tests is outside the scope of this book.

Rated frequency. There is evidence that the interrupting capacity of circuit breakers, especially that of high-speed breakers, is considerably less at 25 cycles than at 60 cycles, but no cognizance of this has yet been taken in the standardization rules.††

Rated continuous current is the greatest r.m.s. 60-c.p.s. load current which can be carried continuously with a temperature rise of each part not exceeding that permitted by the rules. For the oil and contacts of oil circuit breakers, the limit of temperature rise is 30 C. At 25 c.p.s. the heating effect of eddy currents is less than it is at 60 c.p.s., and, for this reason, breakers having large continuous-current ratings (600 amp. and over) at 60 c.p.s. may be given still larger ratings at 25 c.p.s., as listed in Table 4.

TABLE 4

CONTINUOUS-CURRENT RATINGS OF CIRCUIT BREAKERS AT 25 CYCLES
(Information from Ref. K8)

60-c.p.s. rating (amp.)	Below 600	600	800	1,200	2,000	3,000	4,000	5,000
25-c.p.s. rating (amp.)	Same as at 60 c.p.s.	700	900	1,400	2,250	3,500	4,500	5,500

Rated interrupting current at rated voltage is the greatest r.m.s. total current (including both a-c. and d-c. components) which can be interrupted safely twice in succession in accordance with the standard duty cycle (discussed below) when the breaker is used on a circuit of rated normal voltage. It is a well-known fact that the short-circuit current of a synchronous machine decays from a high initial value to a lower sustained value with a time constant of the order of several seconds. The current at the instant when the breaker contacts part governs; it should not exceed the rated current-interrupting capacity under the worst fault condition. For a given fault, the current to be interrupted depends upon the sum of the relay time and the breaker opening time. The opening time is approximately 4 cycles for an 8-cycle breaker, 3 cycles for a 5-cycle breaker, 2 cycles for a 3-cycle breaker, and 1 cycle for a 2-cycle breaker.

---

††See discussion of Ref. I31 by A. W. Hill.

The interrupting capacity required of a breaker is not necessarily related to the continuous-current capacity required of it. For example, on a generating-station bus to which are connected several generators, several transmission lines, and a house-service transformer, the circuit breaker for the house-service transformer may have the lowest load current of all the breakers on the bus. In spite of this, it may be required to interrupt the largest short-circuit current of all the breakers; for, in case of a short circuit on the high-voltage side of this transformer, the breaker must interrupt current fed by all the generators and all the transmission lines, whereas, in case of a short circuit on a generator or line, the breaker must interrupt current fed from all generators and lines *except the faulted one.*

Rated interrupting kva. of a three-phase circuit breaker is $\sqrt{3}$ times rated voltage in kilovolts times the rated interrupting current in amperes at rated voltage. The rated interrupting kva. is more commonly quoted than the rated interrupting current. Standard breakers are manufactured with interrupting ratings as high as 10,000,000 kva. (10,000 Mva.).

Rated maximum interrupting current. If a breaker is used on a circuit the normal voltage of which is lower than the rated voltage of the breaker, the rated interrupting current is assumed to be increased in inverse proportion to the voltage. In other words, the rated interrupting kva. is assumed to remain constant as the voltage is reduced. However, regardless of how much the voltage is reduced, the rated interrupting current does not exceed the rated maximum interrupting current. With some forms of air circuit breakers, the rated maximum interrupting current is only slightly greater than the rated interrupting current at rated voltage. Such breakers are more nearly constant-current-interrupting devices than constant-kva.-interrupting devices as the circuit voltage changes.

Duty cycle. The rated interrupting capacity of a breaker is based on a standard duty cycle consisting of two unit operations separated by a time interval. Each unit operation consists of closure of the breaker, immediately followed by opening (usually abbreviated CO). The interval between the two unit operations is 15 sec. for oiltight breakers and 2 min. for nonoiltight breakers.‡‡ (Breakers having interrupting ratings of 50,000 kva. and above are oiltight; those below 50,000 kva. may be nonoiltight.) The interrupting capacity of standard circuit breakers when used on special duty cycles may be calculated by multiplying the rated interrupting capacity by a derating factor given in the N.E.M.A. Standards.[K9]

Rated short-time current. Two short-time current ratings are given, the *rated momentary current,* specifying the greatest current which can be safely withstood for a period of 1 sec. or less, and the *rated 4-sec. current,* specifying the greatest current which can be safely withstood for a period longer than 1 sec. but not exceeding 4 sec. Both are r.m.s. total current (a-c. and d-c. components). Short-time current ratings are based on mechanical or thermal limitations.

Rated interrupting time is the maximum time for interruption of any current not exceeding the rated interrupting current of the breaker. Some older designs of oil circuit breakers have a longer arcing time at low currents than at high currents because the stream of oil and gases which extinguishes the arc is produced by pressure generated by the arc itself or by another arc. The rated interrupting time is based upon the maximum time of interruption of currents in the range from 25 to 100% of the rated interrupting current. Newer designs of both oil and air circuit breakers in which the stream of cooling fluid is independent of the arc current have interrupting times which are almost independent of current, and the above-mentioned restriction may not apply. In all a-c. circuit breakers, however, the arcing time varies through a range of at least one-half cycle, depending on the point in the cycle when the contacts part, because the arc is not extinguished until approximately the time of a normal current zero. For the same reason, the average and maximum interrupting times of a breaker are increased by a decrease of the normal power frequency. There is some argument as to whether the interrupting time of a circuit breaker with high resistance shunting the arcing contacts should include the time during which a low current flows in the resistors after the main arc has been interrupted. This low current is not detrimental except that, if the breaker is to be rapidly reclosed, the resistor current may delay deionization of the fault arc and thus increase the minimum permissible reclosing time.

Interrupting performance (quoted from A.S.A. Standards):[K6]

---

‡‡Before 1934, the interval was 2 min. for all oil circuit breakers.

> An oil circuit breaker shall perform at or within its rated interrupting current without emitting flame or an appreciable quantity of oil. For breakers of the non-oil-tight construction only, the emission of limited quantities of oil may be permitted.
>
> An oilless circuit breaker shall perform at or within its rated interrupting current without emitting appreciable flame.
>
> At the end of any performance at or within its interrupting rating the circuit breaker shall be in the following condition:
>
> > *Mechanical:* The breaker shall be substantially in the same mechanical condition as at the beginning.
> >
> > *Electrical:* The breaker shall be capable of withstanding rated voltage in the open position and of carrying rated continuous current at rated voltage for a limited time, but not necessarily without exceeding rated temperature rise. After a performance at or near its interrupting rating, it is not to be inferred that the breaker can meet its interrupting rating without inspecting and, if necessary, making repairs.

It is apparent from the foregoing statements that an oil circuit breaker is not expected to perform its intended function with the same freedom from maintenance trouble that is expected of most other pieces of electrical apparatus, for example, motors and transformers. There is also room for difference of opinion in interpreting such phrases as "appreciable quantity," "limited quantities," and "substantially in the same mechanical condition."

Rated making current of a power-operated circuit breaker is the maximum r.m.s. total current against which the breaker can be closed and immediately opened without welding of contacts or excessive damage to the breaker or to the contacts.

Rated latching current of a power-operated circuit breaker is the maximum r.m.s. total current against which the breaker can be closed and latched. Standard values of rated making and latching currents have not yet been established.

Testing circuit breakers. Development of improved circuit breakers requires suitable testing facilities. Several manufacturers have high-power testing laboratories for this purpose. It cannot be expected, however, that the short-circuit power available in a laboratory will ever suffice for testing the largest breakers at their rated interrupting capacity. Consequently, means have been devised to get the effect of a higher power. One of the means is to decrease the effective opening time of the tested breaker by initiating tripping of this breaker before applying the short circuit through another breaker. Thus the tested breaker opens while the rapidly decaying subtransient and d-c. components of short-circuit current are still large. Tests are commonly made on only one pole of a three-pole breaker at a time, although the kva. rating is a three-phase value. The single-pole test is surely valid for breakers having separate pole structures, as most large breakers have, but not for single-tank three-pole oil circuit breakers, which are subjected to a greater stress when all three poles interrupt current than when only one does. Most oil circuit breakers have two interrupters in series per pole, and each interrupter can be tested individually at half voltage. The half-pole test is valid if, with the breaker in normal service, the recovery voltage divides equally between the two interrupters and if the pressure in the tank with arcs in both interrupters is not excessive. Doubt on the latter score can be removed by use of the three-phase test on one pole, the test connections being as shown in Fig. 29. Some types of multibreak air-blast breakers allow tests on one of n interrupters in series at $1/n$ of rated voltage. Some work has been done on circuits in which the high current to be interrupted is supplied from a low-voltage source and the recovery voltage is supplied from a separate source. The validity of such indirect tests has not been firmly established.[135-8]

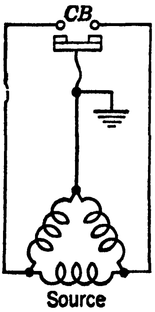


FIG. 29. Three-phase test on one pole of a circuit breaker *CB*.

Occasionally large circuit breakers are tested on power systems where higher values of short-circuit power are available than in testing stations. It is generally true, however, that the rate of rise of recovery voltage is not so great in field tests as in laboratory tests. The test breaker is commonly pretripped in field tests not only to increase the interrupted kva. but also to lessen the shock to the power system. One-line-to-ground faults are preferred for the same two reasons.

Multielement magnetic oscillographs are used in circuit-breaker tests to record the current through and the voltage across each tested pole of the breaker, the current in the trip coil, and the travel of the lift rod. Cathode-ray oscillographs are better than the magnetic type for showing recovery voltages having high-frequency components.

Breakers should be tested as to their ability not only to interrupt short-circuit currents but also to break line-charging (capacitive) currents without production of dangerous overvoltages caused by successive delayed restrikes.

Simplified calculation of fault currents for circuit-breaker application. The selection of a circuit breaker of proper rating for a given location on a power system necessitates the calculation of the maximum fault current which the breaker may be required to interrupt and of the maximum current which it may have to carry momentarily. The exact calculation of fault currents, including both the a-c. and d-c. components and their decrements, is so complicated as to be impractical. However, a simplified method has been evolved by the A.I.E.E. Committee on Protective Devices and recommended by them for general use.[L1-4] This method, in so far as it applies to circuit breakers, is described below, with no attempt to justify it.

To determine the required interrupting capacity of a circuit breaker, first determine the highest value of initial r.m.s. alternating current for any type and location of fault. It is sufficient to consider three-phase faults, for which the current is given by E/X_1, and line-to-ground faults, for which the current is given by $3E/(2X_1 + X_0)$. Use whichever result is greater, but when R_0 is greater than $5X_1$, no consideration need be given to a line-to-ground fault. In these expressions, E is the normal line-to-neutral voltage, X_1 is the positive-sequence reactance, X_0 is the zero-sequence reactance, and R_0 is the zero-sequence resistance of the system as viewed from the point of fault when the maximum capacity of synchronous machines is connected; all these quantities being in per unit on a common base. The sequence reactances may be found by the use of an a-c. or d-c. calculating board or by network reduction, as described in Chapter III, Vol. I. In the computation of X_1, synchronous generators are represented by their subtransient reactances (discussed in Chapter XII, Vol. III)—or, for hydroelectric generators without damper windings, by 75% of their transient reactances—and synchronous motors, by their transient reactances. Induction machines are ignored.

After the highest value of initial r.m.s. alternating current has been calculated, as described above, it is multiplied by a factor to take account of the d-c. component of current and the decrements of both the a-c. and d-c. components. The decrements, of course, depend upon the interrupting time and, hence, on the breaker speed. The recommended multiplying factors for ordinary cases are as follows:

8-cycle or slower breaker	1.0
5-cycle breaker	1.1
3-cycle breaker	1.2
2-cycle breaker	1.4

However, for breakers on a generator bus where the three-phase short-circuit kilovolt-amperes exceed 500,000 (before the application of any multiplying factor) all the factors given above are increased by 0.1. The resulting value is the current in the fault itself. If the entire fault current does not go through the breaker under consideration, the portion of the current which does go through it must be computed.

To determine the required rated momentary current of a circuit breaker, calculate the highest value of initial r.m.s. alternating current, as described above, except use subtransient reactances of all machines, including induction motors. Then multiply the value of current so obtained by the factor 1.6. (However, at 5 kv. and below, unless current is fed to the fault predominantly by directly connected machines or through reactors, the factor 1.4 may be used.)

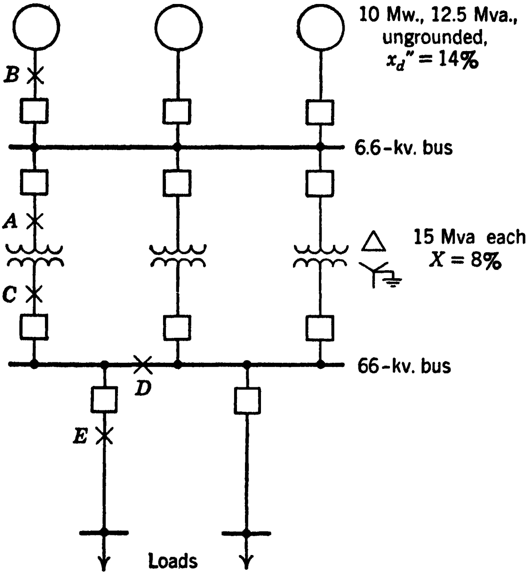


FIG. 30. Power system used for illustrating circuit-breaker application (Example 1). Values of reactance are based on the apparatus rating.

EXAMPLE 1

Select from Tables 1 and 2 suitable oil circuit breakers for the power system of Fig. 30. The low-voltage breakers are to be of the indoor type.

Solution. On a 37.5-Mva. base the reactances in per unit are as follows:

Each generator (subtransient)	$0.14 \times 37.5/12.5 = 0.42$
Each transformer	$0.08 \times 37.5/15 = 0.20$

Unit current at 6.6 kv. is $37.5 \times 10^6/(\sqrt{3} \times 6{,}600) = 3{,}280$ amp.; at 66 kv., 328 amp.

Transformer low-voltage breakers. The fault location giving maximum fault current through these breakers is at A, to which fault current is fed directly from all generators. Since the 6.6-kv. system is ungrounded, line-to-ground faults need not be considered. For a three-phase fault at A, $X_1 = 0.42/3 = 0.14$ per unit, and the initial r.m.s. alternating fault current is $E/X_1 = 1/0.14 = 7.14$ per unit, or $7.14 \times 3{,}280 = 23{,}400$ amp., or $7.14 \times 37.5 = 268$ Mva. Athough the breaker is on a generator bus, the fault current does not exceed 500 Mva.; therefore, for an 8-cycle breaker, the multiplying factor is 1.0, and the current to be interrupted is the same as the initial r.m.s. alternating current. The momentary current is $1.6 \times 23{,}400 = 37{,}400$ amp. The full-load current of the transformer is $3{,}280 \times 15/37.5 = 1{,}310$ amp. Inspection of Table 1 shows that no 7.2-kv. oil circuit breaker has enough interrupting capacity, the largest being 100 Mva. Therefore a 13.8- or 14.4-kv. breaker must be used. The breaker in line 10 of the table is suitable, having a rated continuous current of 2,000 amp. and an interrupting rating of 500 Mva. The current which must be interrupted at 6.6 kv. (23,400 amp.) exceeds the rated interrupting current (21,000 amp.) of this breaker at rated voltage, but, as it does not exceed the rated maximum interrupting current of 44,000 amp. or the rated interrupting kva., the breaker is adequate. The expected momentary current (37,400 amp.) is also well below the rated momentary current of the breaker (70,000 amp.).

Generator breakers. The worst fault location for these breakers is at B. Current is fed to a fault at B through one generator's circuit breaker from the other two generators. Therefore the fault current in the breaker is two-thirds of that calculated above for the transformer low-voltage breakers. The current to be interrupted is $\frac{2}{3} \times 23{,}400 = 15{,}600$ amp., or $\frac{2}{3} \times 268 = 179$ Mva. The momentary current is $\frac{2}{3} \times 37{,}400 = 25{,}000$ amp. The full-load current of the generator is $3{,}280/3 = 1{,}090$ amp. The 13.8-kv. breaker in line 8 of Table 1 can be used; it is rated at 1,200 amp. continuous current, 250 Mva. interrupting capacity, 36,000 amp. maximum interrupting current, and 60,000 amp. momentary current. Consideration should be given, however, to making the generator breakers the same as the transformer breakers to allow for future expansion of the station and to simplify the stocking of spare parts.

Line breakers. The worst fault location is at E, the near end of the line. Here $X_1 = 0.42/3 + 0.20/3 = 0.21$ per unit, and $X_0 = 0.20/3 = 0.07$ per unit. For a three-phase fault, the current is $E/X_1 = 1/0.21 = 4.76$ per unit; and for a line-to-ground fault, $3E/(2X_1 + X_0) = 3/0.48 = 6.25$ per unit, which is higher than for a three-phase fault. All the current goes through the line breaker. The multiplying factor is 1.0. The current to be interrupted is $6.25 \times 328 = 2{,}050$ amp., or $6.25 \times 37.5 = 234$ Mva. The momentary current is $1.6 \times 6.25 \times 328 = 3{,}280$ amp. The full-load current of the line will be taken as that of two transformer banks in parallel, $2 \times 131 = 262$ amp. The smallest 69-kv. breaker listed (on line 17 of Table 2) is suitable.

Transformer high-voltage breakers. With all transformer banks in service, a fault at C would take the same current as the fault at E which was just considered, but only two-thirds of this current would go through the transformer breaker. With two banks switched out and a fault at D, all the fault current would go through the remaining bank and its circuit breaker, but the current would be less than the fault current with all transformers connected. Since the smallest 69-kv. breaker was selected for the transmission line, the same size would be used on the 66-kv. side of the transformers, and it is needless to calculate the current.

REFERENCES

A. Circuit Breakers—General

1. Trade literature of General Electric Co., Schenectady, N. Y.; Westinghouse Electric Corporation, East Pittsburgh, Pa.; Allis-Chalmers Manufacturing Co., Milwaukee, Wis.; and Pacific Electric Manufacturing Corporation, San Francisco, Calif.

2. M. H. Hobbs, J. W. Simpson, H. A. Travers, and L. E. Markle, "Switchgear and Control Equipment," Sec. 12 of *Electrical Engineers' Handbook—Electric Power*, edited by Harold Pender and William A. Del Mar, New York, John Wiley & Sons, 4th edition, 1949.

3. D. C. Prince, "European Switchgear Developments," *Elec. Eng.*, vol. 57, pp. 155–63, April, 1938.

4. A.I.E.E. Committee on Protective Devices, "Ten Years of Progress in Circuit Interrupters," *Elec. Eng.*, vol. 60, pp. 523–37, November, 1941.

5. E. L. Harder and J. C. Cunningham, "Relay and Circuit-Breaker Application," Chap. 10 of *Electrical Transmission and Distribution Reference Book* by Central Station Engineers of the Westinghouse Electric & Manufacturing Co., East Pittsburgh, 1st edition, 1942; 3rd edition, 1944.

6. H. P. Young, *Electric Power System Control*, London, Chapman & Hall, Ltd., 1st edition, 1942; 2nd edition, 1946. Chap. VI, "Circuit Breakers and Circuit Interruption."

7. J. B. MacNeill, "Switchgear Practice in Europe and America," *Elec. Eng.*, vol. 61, pp. 609–13, December, 1942.

8. A.I.E.E. Committee on Protective Devices, "Bibliography on Circuit-Interrupting Devices, 1928–40," *A.I.E.E. Trans.*, vol. 61, pp. 1077–100, 1942.

9. C. H. Kreger, "Metal-Clad Unit-Type Switchgear for 33-Kv. Service," *A.I.E.E. Trans.*, vol. 65, pp. 360–8, June, 1946. Disc., pp. 509–10.

10. Hans Thommen, "Problems Connected with the Rupturing of A.C. Currents at Very High Voltages up to 400 Kv ," *C.I.G.R.E.*, report 109, 1946.

11. M. H. Hobbs, "A Brief Review of Switchgear and Circuit Breaker Practice in the United States," *A.I.E.E. Trans.*, vol. 67, part II, pp. 893–7, 1948. Disc., pp. 897–8.

12. Archer E. Knowlton (Editor-in-Chief), *Standard Handbook for Electrical Engineers*, 8th edition, New York, McGraw-Hill Book Co., 1949. Pages 1019–36.

13. Erwin Salzer, "Fundamentals of A-C Circuit Interruption," *Allis-Chalmers Elec. Rev.*, vols. 13–4, 1948–9:

   a. Part I, vol. 13, no. 2, pp. 20–4, 1948.
   b. Part II, vol. 13, no. 3, pp. 20–5, 1948.

c. Part III, vol. 13, no. 4, pp. 18–23, 1948.
d. Part IV, vol. 14, no. 1, pp. 28–34, 1949.
e. Part V, vol. 14, no. 2, pp. 24–34, 1949.
f. Part VI, vol. 14, no. 3, pp. 26–38, 1949.

Republished in pamphlet form, with revisions, by Allis-Chalmers Manufacturing Co., Milwaukee, 1950.

14. Robert H. Nau, "Modern-Type High-Power Circuit Breakers," *Proc. Midwest Power Conference* (Chicago), vol. 12, pp. 53–60, 1950.

B. Arc Theory

1. J. Slepian, "Extinction of an A-C. Arc," *A.I.E.E. Trans.*, vol. 47, pp. 1398–407, October, 1928. Disc., pp. 1407–8.

2. E. B. Wedmore, W. B. Whitney, and C. E. R. Bruce, "An Introduction to Researches on Circuit Breaking," *I.E.E. Jour.* (London), vol. 67, pp. 557–78, May, 1929. Disc., pp. 578–93.

3. J. Biermanns, "Hochleistungschalter ohne Öl (High-Capacity Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 50, pp. 1073–9, July 25, 1929.

4. J. Slepian, "Extinction of a Long A-C. Arc," *A.I.E.E. Trans.*, vol. 49, no. 2, pp. 421–30, April, 1930. Disc., pp. 441–6.

5. C. E. R. Bruce, "The Distribution of Energy Liberated in an Oil Circuit Breaker; with a Contribution to the Study of the Arc Temperature," *I.E.E. Jour.* (London), vol. 69, pp. 557–82, May, 1931. Disc., pp. 582–90.

6. T. E. Browne, Jr., "Extinction of A-C. Arcs in Turbulent Gases," *A.I.E.E. Trans.*, vol. 51, pp. 185–91, March, 1932. Disc., pp. 191–7.

7. F. G. Ruegg, J. Kopeliowitsch, J. Biermanns, O. Mayr, A. Roth, and F. Kesselring, "Die Resultate neuerer Forschungen über den Abschaltvorgang im Wechselstromlichtbogen und ihre Anwendung im Schalterbau—Oelschalter, Druckluftschalter, Expansionsschalter (Results of Recent Investigations of the Interrupting Phenomena in Alternating-Current Arcs and Their Application in the Design of Circuit Breakers—Oil, Compressed-Air, and Expansion Circuit Breakers)," *Schweizerischer Elektrotechnischer Verein* (*Association Suisse des Électriciens*) *Bull.* (Zurich), vol. 23, no. 22, pp. 565–92, October 26, 1932; no. 23, pp. 605–24, November 9, 1932. Disc., pp. 625–9.

8. Joseph Slepian, "The Electric Arc in Circuit Interrupters," *Franklin Inst. Jour.*, vol. 214, pp. 413–42, October, 1932.

9. R. C. Van Sickle and W. E. Berkey, "Arc Extinction Phenomena in High Voltage Circuit Breakers—Studied With a Cathode-Ray Oscillograph," *A.I.E.E. Trans.*, vol. 52, no. 3, pp. 850–7, September, 1933. Disc., pp. 857–60.

10. Bodo von Borries and Werner Kaufmann, "Abschaltversuche an Hochleistungsschaltern—Untersuchungen mit dem Kathodenstrahl-Oszillographen (Interruption Tests on High-Power Circuit Breakers—Investigations with the Cathode-Ray Oscillograph)," *V.D.I. Zeitschrift* (Berlin), vol. 79, pp. 597–604, May 18, 1935.

11. Bernhard Kirschstein and Floris Koppelmann, "Der elektrische Lightbogen in schnellströmendem Gas (The Electric Arc in Fast-Flowing Gas)," *Wissenschaftliche Veröffentlichungen aus den Siemens-Werken* (Berlin), vol. 16, no. 1, pp. 51–71, March 17, 1937; no. 3, pp. 26–55, October 8, 1937.

12. Bernhard Kirschstein and Floris Koppelmann, "Beitrag zur Minimumtheorie der Lichtbogensäule, Vergleich zwischen Theorie und Erfahrung

(Contribution to the Minimum Theory of the Arc Column—Comparison of Theory with Experience)," *Wissenschaftliche Veröffentlichungen aus den Siemens-Werken* (Berlin), vol. 16, no. 3, pp. 56–68, October 8, 1937.

13. Joseph Slepian, "Displacement and Diffusion in Fluid-Flow Arc Extinction," *A.I.E.E. Trans.*, vol. 60, pp. 162–7, April, 1941. Disc., pp. 643–5.

14. E. W. Boehne, "The Geometry of Arc Interruption," *Gen. Elec. Rev.*, vol. 44, pp. 207–16, April, 1941.

15. E. W. Boehne, "The Geometry of Arc Interruption," *A.I.E.E. Trans.*, vol. 60, pp. 524–32, 1941. Disc., pp. 675–6.

16. O. Mayr, "Über die Theorie des Lichtbogens und seiner Löschung (On the Theory of the Arc and Its Extinction)," *E.T.Z.* (Berlin), vol. 64, pp. 645–52, December 16, 1943.

17. O. Mayr, "Beiträge zur Theorie des statischen und des dynamischen Lichtbogens (Contribution to the Theory of the Static and the Dynamic Arc)," *Archiv für Elektrotechnik* (Berlin), vol. 37, pp. 588–608, December 31, 1943.

18. T. E. Browne, Jr., "Dielectric Recovery by an A-C Arc in an Air Blast," *A.I.E.E. Trans.*, vol. 65, pp. 169–76, March, 1946. Disc., pp. 507–9.

19. E. Vogelsanger, "Researches on Arc Quenching in Low-Oil-Content Circuit Breakers," *C.I.G.R.E.*, report 121, 1946.

20. W. M. Leeds and R. C. Van Sickle, "The Interruption of Charging Current at High Voltage," *A.I.E.E. Trans.*, vol. 66, pp. 373–80, 1947. Disc., pp. 381–2.

21. Laurel J. Lewis, "Circuit Breaker Current Measurements during Reignitions and Recovery," *A.I.E.E. Trans.*, vol. 66, pp. 1253–7, 1947. Disc., p. 1257.

22. T. E. Browne, Jr., "A Study of A-C Arc Behavior near Current Zero by Means of Mathematical Models," *A.I.E.E. Trans.*, vol. 67, part I, pp. 141–50, 1948. Disc., pp. 150–3.

23. See item A13*a*.

C. Recovery Voltage

1. H. Gubler, "Errechnung der Eigenfrequenz der wiederkehrenden Spannung und ihre Bedeutung fur die Abschaltleistung (Calculation of the Natural Frequency of the Recovery Voltage and Its Significance to the Interrupting Capacity)," *V.D.E. Fachberichte* (Berlin), vol. 5, pp. 48–51, 1931.

2. F. Kesselring, "Netzkonfiguration und Abschaltleistung (System Configuration and Interrupting Capacity)," *V.D.E. Fachberichte* (Berlin), vol. 5, pp. 51–4, 1931.

3. Robert H. Park and Wilfred F. Skeats, "Circuit Breaker Recovery Voltages—Magnitudes and Rates of Rise," *A.I.E.E. Trans.*, vol. 50, pp. 204–38, March, 1931. Disc., pp. 238–9.

4. J. Kopeliowitsch, "Influence de la forme de la tension de rupture sur le travail des disjoncteurs (Influence of the Transient Recovery Voltage on Circuit-Breaker Performance)," *Schweizerischer Elektrotechnischer Verein (Association Suisse des Électriciens) Bull.* (Zurich), vol. 22, pp. 312–7, June 24, 1931.

5. S. S. Attwood, W. G. Dow, and W. Krausnick, "Reignition of Metallic A-C. Arcs in Air," *A.I.E.E. Trans.*, vol. 50, pp. 854–68, September, 1931.

6. E. J. Poitras, H. P. Kuehni, and W. F. Skeats, "Oil Circuit Breaker and Voltage Recovery Tests," *A.I.E.E. Trans. (Elec. Eng.)*, vol. 54, pp. 170–8, February, 1935.

7. R. C. Van Sickle, "Breaker Performance Studied by Cathode Ray Oscillo-

grams," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 54, pp. 178–84, February, 1935.

8. C. H. FLURSCHEIM, "Some Notes on Rates of Rise of Restriking Voltage Subsequent to Interruption of Alternating-Current Power Circuits," *I.E.E. Jour.* (London), vol. 76, pp. 323–37, March, 1935.

9. E. W. BOEHNE, "The Determination of Circuit Recovery Rates," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 54, pp. 530–9, May, 1935.

10. GEORG HAMEISTER, "Der Anstieg der wiederkehrenden Spannung nach Kurzschlussabschaltungen im Netz (The Rise of the Recovery Voltage after Short-Circuit Interruption in Systems)," *E.T.Z.* (Berlin), vol. 57, pp. 1025–8, September 3, 1936; pp. 1052–4, September 10, 1936.

11. H. TRENCHAM and K. J. R. WILKINSON, "Restriking Voltage and Its Import in Circuit-Breaker Operation," *I.E.E. Jour.* (London), vol. 80, pp. 460–8, May, 1937. Disc., pp. 468–89.

12. L. GOSLAND, "Restriking Voltage Characteristics and Fault Currents," *World Power* (London), vol. 27, pp. 160–72, May, 1937.

13. R. D. EVANS and A. C. MONTEITH, "System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 56, pp. 695–705, June, 1937. Disc., pp. 1308–12.

14. W. WANGER and J. K. BROWN, "Calculation of the Oscillations of the Recovery Voltage after the Rupture of Short Circuits," *Brown Boveri Rev.* (Baden), vol. 24, pp. 283–302, November, 1937.

15. E. KROHNE and F. KESSELRING, "Recherches faites en 1936 sur la tension de rétablissement et la rigidité diélectrique (Investigations Made in 1936 of Recovery Voltage and Dielectric Strength)," *C.I.G.R.E.*, 1937, vol. 1, report 112, 16 pp.

16. L. GOSLAND, "Measurements and Calculations on Restriking-Voltage Transients at a Substation Fed by Single-Core Cables," *I.E.E. Jour.* (London), vol. 84, pp. 269–86, February, 1939.

17. L. GOSLAND, "Restriking Voltage at a Transformer Substation Supplied by a Long Feeder System," *I.E.E. Jour.* (London), vol. 84, pp. 672–82, June, 1939.

18. C. CONCORDIA and W. F. SKEATS, "Effect of Restriking on Recovery Voltage," *A.I.E.E. Trans.*, vol. 58, pp. 371–5, August, 1939. Disc., pp. 375–6.

19. EDITH CLARKE, S. B. CRARY, and H. A. PETERSON, "Overvoltages during Power-System Faults," *A.I.E.E. Trans.*, vol. 58, pp. 377–85, August, 1939. Disc., p. 385.

20. R. D. EVANS, A. C. MONTEITH, and R. L. WITZKE, "Power-System Transients Caused by Switching and Faults," *A.I.E.E. Trans.*, vol. 58, pp. 386–94, August, 1939. Disc., pp. 394–7.

21. R. C. VAN SICKLE, "Influence of Resistance on Switching Transients," *A.I.E.E. Trans.*, vol. 58, pp. 397–404, August, 1939. Disc., p. 404.

22. HAROLD A. PETERSON, "Power-System Voltage-Recovery Characteristics," *A.I.E.E. Trans.*, vol. 58, pp. 405–11, August, 1939. Disc., pp. 411–3.

23. L. V. BEWLEY, "Equivalent Circuits of Transformers and Reactors to Switching Surges," *A.I.E.E. Trans.*, vol. 58, pp. 797–802, 1939.

24. L. GOSLAND, "Restriking-Voltage Characteristics Under Various Fault Conditions at Typical Points on the Network of a Large City Supply Authority," *I.E.E. Jour.* (London), vol. 86, pp. 248–74, March, 1940.

25. L. GOSLAND and W. F. M. DUNNE, "Calculation and Experiment on Transformer Reactance in Relation to Transients of Restriking Voltage," *I.E.E. Jour.* (London), vol. 87, pp. 163–77, August, 1940.

26. G. W. Dunlap, "The Recovery-Voltage Analyzer for Determination of Circuit Recovery Characteristics," *A.I.E.E. Trans.*, vol. 60, pp. 958–62, November, 1941. Disc., p. 1391.

27. H. P. St. Clair and J. A. Adams, "Transient Recovery-Voltage Characteristics of Electric-Power Systems," *A.I.E.E. Trans.*, vol. 61, pp. 666–9, September, 1942. Disc., pp. 1016–7.

28. J. A. Adams, W. F. Skeats, R. C. Van Sickle, and T. G. A. Sillers, "Practical Calculation of Circuit Transient Recovery Voltages," *A.I.E.E. Trans.*, vol. 61, pp. 771–9, November, 1942. Disc., pp. 1017–9.

29. R. C. Van Sickle, "Transient Recovery Voltages and Circuit-Breaker Performance," *A.I.E.E. Trans.*, vol. 61, pp. 804–13, November, 1942. Disc., pp. 1014–6.

30. T. W. Schroeder, E. W. Boehne, and J. W. Butler, "Tests and Analysis of Circuit-Breaker Performance When Switching Large Capacitor Banks," *A.I.E.E. Trans.*, vol. 61, pp. 821–31, November, 1942. Disc., pp. 1020–6.

31. R. L. Witzke, "Power System Voltages and Currents during Abnormal Conditions," Chap. 15 of *Electrical Transmission and Distribution Reference Book* by Central Station Engineers of the Westinghouse Electric & Manufacturing Co., East Pittsburgh, 1st edition, 1942.

32. Lloyd F. Hunt, E. W. Boehne, and H. A. Peterson, "Switching Overvoltage Hazard Eliminated in High-Voltage Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 62, pp. 98–106, February, 1943. Disc., pp. 418–22.

33. Hans Thommen, "Problems Connected with the Rupturing of A.C. Currents at Very High Voltages up to 400 Kv," *C.I.G.R.E.*, report 109, 1946.

34. E. Vogelsanger, "A Study of the Maximum Currents and Voltages Which Can Stress a Circuit-Breaker in a Monophase or Polyphase System During the Rupture of Short-Circuits," *C.I.G.R.E.*, report 119, 1946.

35. A. H. Pollard, "Use of Resistance Switching in the Interruption of High Voltage Circuits," *C.I.G.R.E.*, report 136, 1946.

36. P. Hammarlund, "Transient Recovery Voltage Subsequent to Short-Circuit Interruption with Special Reference to Swedish Power Systems," *Ingeniörsvetenskapsakademien Handlingar* (*Proc. Royal Swedish Academy of Eng. Sciences*, Stockholm), no. 189, 264 pp., 1946.

37. P. E. Hammarlund and O. Johansen, "Transient Recovery Voltage Subsequent to Short-Circuit with Special Reference to Swedish Power Systems," *C.I.G.R.E.*, report 107, 1948.

38. S. Rambaut, "Determination of the Voltage across the Terminals of a Circuit Breaker as a Function of the Current Interrupted, by Means of Rupturing Tests with Small Currents," *C.I.G.R.E.*, report 111, 1948.

39. D. Th. J. ter Horst, "The Natural Frequencies in the 150 Kv Transmission System of the Netherlands," *C.I.G.R.E.*, report 123, 1948.

40. H. Thommen, "On the Question of the Electrodynamic Oscillations Stressing High-Power Circuit Breakers," *C.I.G.R.E.*, report 125, 1948.

41. H. Puppikofer, "Report on the Activities of the International Committee for the Study of Circuit Breakers, from 1st July 1946 to 1st July 1948," *C.I.G.R.E.*, report 138, 1948.

42. F. Kurth, "Natural Frequency of the Recovery Voltage in Alternating Current Networks," *C.I.G.R.E.*, report 139, 1948. Measurement in the network upon disconnecting a shunt reactor.

43. See item A13c.

D. Oil Circuit Breakers

1. J. B. MacNeill, "Improvements in Moderate Capacity Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 47, pp. 793–7, July, 1928. Disc., pp. 797–8.

2. J. Kopeliowitsch, "Neuere Forschungsergebnisse über Vorgänge beim Schalten unter Oel (Recent Research on Current Interruption under Oil)," *Schweizerischer Elektrotechnischer Verein (Association Suisse des Électriciens) Bull.* (Zurich), vol. 19, no. 17, pp. 541–77, September 1, 1928.

3. B. F. Bardo, "Operating Experience with High-Speed Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 47, pp. 1293–6, October, 1928. Disc., pp. 1311–22.

4. K. Sachs, "The Development in the Design of Brown Boveri Oil Circuit Breakers," *Brown Boveri Rev.* (Baden), vol. 17, pp. 56–63, January, 1930.

5. L. W. Dyer, "Field Tests on Deïon Grid Breakers," *Elec. Wld.*, vol. 95, pp. 786–92, April 19, 1930.

6. B. P. Baker and H. M. Wilcox, "The Use of Oil in Arc Rupture with Special Reference to System Stability," *A.I.E.E. Trans.*, vol. 49, pp. 431–41, April, 1930. Disc., pp. 441–6. De-ion grid.

7. R. Wilkins and E. A. Crellin, *High-Voltage Oil Circuit Breakers*, New York, McGraw-Hill Book Co., 1930.

8. D. C. Prince and E. J. Poitras, "Oil-Blast Breaker Theory Proved Experimentally," *Elec. Wld.*, vol. 97, pp. 400–4, February 28, 1931.

9. W. M. Leeds, "Pressure Phenomena in Oil Circuit Breakers," *Elec. Jour.*, vol. 28, pp. 152–6, March, 1931.

10. J. B. MacNeill, "Development Trends in Circuit Interrupters," *Elec. Eng.*, vol. 50, pp. 260–5, April, 1931.

11. D. C. Prince and W. F. Skeats, "The Oil-Blast Circuit Breaker," *A.I.E.E. Trans.*, vol. 50, pp. 506–12, June, 1931. Disc., pp. 521–31.

12. D. C. Prince and W. E. Paul, "Oil Blast Extended to Other Breakers," *Elec. Wld.*, vol. 98, pp. 499–501, September 19, 1931.

13. W. K. Rankin, "The Impulse High-Speed Circuit Breaker," *Gen. Elec. Rev.*, vol. 34, pp. 553–8, October, 1931.

14. D. C. Prince and E. B. Noel, "Efficacy of Oil-Blast Principle Confirmed by Photography," *Gen. Elec. Rev.*, vol. 34, pp. 722–4, December, 1931.

15. W. M. Leeds, "Arc Energy Liberation Fixes Breaker Pressures," *Elec. Wld.*, vol. 98, pp. 1138–41, December 26, 1931.

16. E. B. Merriam, "Modern High Speed Oil Circuit Breakers," *Canadian Elec. Assoc.* (Montreal) *41st Convention Proc.*, pp. 307–23, 1931.

17. D. C. Prince, "The Theory of Oil-Blast Circuit Breakers," *A.I.E.E. Trans.*, vol. 51, pp. 166–70, March, 1932. Disc., pp. 191–7.

18. R. M. Spurck, "Practical Application of the Oil-Blast Principle of Circuit Interruption," *A.I.E.E. Trans.*, vol. 51, pp. 171–6, March, 1932. Disc., pp. 191–7.

19. R. C. Van Sickle and W. M. Leeds, "Recent Developments in Arc Rupturing Devices," *A.I.E.E. Trans.*, vol. 51, pp. 177–84, March, 1932. Disc., pp. 191–7.

20. A. W. Hill, "Roseland Substation 3,000,000-Kv-a Circuit Breakers," *Elec. Jour.*, vol. 29, pp. 383–5, August, 1932.

21. H. E. Strang, "Oil-Blast Circuit Breakers of Medium Capacity," *Gen. Elec. Rev.*, vol. 36, pp. 94–8, February, 1933.

22. J. Biermanns, "Die neueste Entwicklung des Ölschalters (The Latest Development of Oil Circuit Breakers)," *V.D.I. Zeitschrift* (Berlin), vol. 77, pp. 673–8, June 24, 1933.

23. G. S. Diehl and W. T. Crook, Jr., "Fighting Oil Breaker Fires" (abstract), *Elec. Wld.*, vol. 102, p. 153, July 29, 1933.

24. D. C. Prince, "Engineering Features of Oil-Blast Action," *Gen. Elec. Rev.*, vol. 36, pp. 361–3, August, 1933.

25. Fritz Kesselring, "Die Freiluft-Expansionsschalter (The Outdoor Expansion Circuit Breaker)," *Siemens Zeitschrift* (Berlin), vol. 13, pp. 309–15, November-December, 1933; (in English) *Siemens Review* (Berlin), vol. 10, pp. 1–7, 1934.

26. D. C. Prince, "Impulse Breaker Has Bushing Dimensions," *Elec. Wld.*, vol. 103, p. 218, February 10, 1934.

27. Fritz Kesselring, "Der Expansionsschalter—Rückblick und Ausblick (The Expansion Breaker—History and Outlook)," *V.D.I. Zeitschrift*, vol. 78, pp. 293–7, March 3, 1934.

28. H. C. Kloninger, "Die Entwicklung der spezifischen Abschaltleistung der Ölschalter (The Development of the Specific Interrupting Capacity in Oil Circuit Breakers)," *Elektrotechnik und Maschinenbau* (Vienna), vol. 52, pp. 286–91, June 24, 1934; pp. 300–3, July 1, 1934.

29. A. C. Schwager, "The Expulsion Oil Circuit Breaker," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 53, pp. 1108–15, July, 1934. Disc., vol. 54, pp. 212–6.

30. "Impulse Circuit Breaker," *Elec. News and Eng.* (Toronto), vol. 43, no. 18, pp. 24–5 and 40, September 15, 1934.

31. D. C. Prince, "Circuit Breakers for Boulder Dam Line," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 54, pp. 366–72, April, 1935. Low-oil-content impulse type.

32. D. C. Prince, "Further Development in Oil-Blast Circuit Breakers," *Gen. Elec. Rev.*, vol. 38, pp. 415–21, September, 1935.

33. Fritz Kesselring, "Forschungsarbeiten im Zusammenhang mit der Entwicklung des Expansionsschalters (Research in the Development of Expansion Breakers)," *Elektrotechnik und Maschinenbau* (Vienna), vol. 53, pp. 493–5, October 20, 1935; pp. 508–14, October 27, 1935.

34. O. Schwenk, "Ölarme Leistungsschalter mit reiner Ölströmung (Oil-Poor Circuit Breaker with Pure Oil Blast)," *E.T.Z.* (Berlin), vol. 57, pp. 229–31, February 27, 1936.

35. L. Heinemeyer, "Spitzenleistungen im Bau von Expansionsschaltern (Outstanding Achievements in the Design of Expansion Breakers)," *E.T.Z.* (Berlin), vol. 57, pp. 281–4, March 5, 1936.

36. H. M. Wilcox and W. M. Leeds, "Circuit Breakers for Boulder Dam Line," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 55, pp. 626–35, June, 1936. Disc., pp. 1250–2, November, 1936.

37. Wilfred F. Skeats, "Special Tests on Impulse Circuit Breakers," *Elec. Eng.*, vol. 55, pp. 710–7, June, 1936.

38. C. D. Ainsworth, "The Ruptor—A Modern High-Efficiency Interrupting Device for Oil Circuit Breakers," *Allis-Chalmers Elec. Rev.*, vol. 1, no. 1, pp. 9–12, September, 1936.

39. L. S. Hobson, "Oil Blast Breaker Arcs Photographed," *Elec. Wld.*, vol. 106, pp. 42–3, 98 (3478–9, 3534), November 7, 1936.

40. "Boulder Canyon Project," *Elec. Jour.*, vol. 33, pp. 490 and 498–9, November, 1936.

41. Wilfred F. Skeats, "Special Tests on Impulse Circuit Breakers," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 55, pp. 710–7, June, 1936. Disc., pp. 1256–7, November, 1936.

42. A. C. SCHWAGER and V. A. TREAT, "Expulsion Breaker Field Tests," *Elec. Wld.*, vol. 107, pp. 37–8, 112 (713–4, 788), February 27, 1937.

43. R. C. VAN SICKLE, "Capacitance Control of Voltage Distribution in Multibreak Breakers," *A.I.E.E. Trans.* (*Elec. Eng.*), vol. 56, pp. 1018–24, August, 1937. Disc., p. 1514, December.

44. R. M. SPURCK and H. E. STRANG, "A New Multibreak Interrupter for Fast-Clearing Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 57, pp. 705–10, December, 1938. Disc., pp. 710–2.

45. J. B. MACNEILL and A. W. HILL, "Multiple-Grid Breakers for High-Voltage Service," *A.I.E.E. Trans.*, vol. 58, pp. 427–31, August, 1939. Disc., pp. 431–4.

46. FRITZ KESSELRING, "Zehn Jahre Expansionsschalter (Ten Years of Expansion Breakers)," *E.T.Z.* (Berlin), vol. 61, pp. 509–15, June 6, 1940.

47. B. P. BAKER, "The Vertical-Flow Interrupter and Its Application to 'Oil-Poor' Circuit Breakers," *A.I.E.E. Trans.*, vol. 60, pp. 440–5, 1941. Disc., pp. 635–8.

48. L. R. LUDWIG and W. M. LEEDS, "A Multiorifice Interrupter for High-Voltage Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 62, pp. 119–25, March, 1943. Disc., pp. 437–9.

49. LLOYD F. HUNT and FRED H. COLE, "Dethermalizing Arc Quenchers," *A.I.E.E. Trans.*, vol. 62, pp. 720–4, November, 1943. Disc., pp. 988–9.

50. A. W. HILL and W. M. LEEDS, "High-Voltage Oil Circuit Breakers for Rapid Reclosing Duty," *A.I.E.E. Trans.*, vol. 63, pp. 113–8, March, 1944. Disc., pp. 452–3.

51. H. L. BYRD and E. B. RIETZ, "A High-Capacity High-Voltage Three-Cycle Oil Circuit Breaker," *A.I.E.E. Trans.*, vol. 64, pp. 160–3, April, 1945. Disc., pp. 463–71.

52. A. W. HILL and W. M. LEEDS, "The Next Step in Interrupting Capacity—5,000,000 Kva," *A.I.E.E. Trans.*, vol. 64, pp. 317–23, June, 1945. Disc., pp. 463–71. Multi-flow De-ion.

53. W. F. SKEATS and E. B. RIETZ, "A New Line of High-Voltage Outdoor Tank-Type Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 65, pp. 224–31, April, 1946. Disc., pp. 502–7.

54. A. THIBAUDAT and J. DE SAEGHER, "Oil Poor Circuit Breakers in Relation to the Problem of Rapid Reclosure," *C.I.G.R.E.*, paper 124, 1946.

55. W. M. LEEDS and G. B. CUSHING, "A 230-Kv 3-Cycle Oil Circuit Breaker for Extra-Heavy Arc Rupturing Duty," *A.I.E.E. Trans.*, vol. 67, part I, pp. 236–42, 1948. Disc., p. 242.

56. E. B. RIETZ, "Unusual Performance of Standard 230-Kv Impulse and Tank-Type Oil Circuit Breakers on Field Tests," *A.I.E.E. Trans.*, vol. 67, part I, pp. 267–70, 1948. Disc., p. 270.

57. C. L. KILLGORE and W. H. CLAGETT, "Field Tests for Development of 10,000,000-Kva 230-Kv Oil Circuit Breakers for Grand Coulee Power Plant," *A.I.E.E. Trans.*, vol. 67, part I, pp. 271–83, 1948. Disc., pp. 283–7.

58. C. L. KILLGORE and W. H. CLAGETT, "Field Tests for Development of Ultra-high Interrupting Capacity 230 Kv Oil Circuit Breakers," *C.I.G.R.E.*, report 130, 1948.

59. See item A13*f*.

60. W. M. LEEDS and R. E. FRIEDRICH, "High-Voltage Oil Circuit Breakers

for 5,000,000 to 10,000,000 Kva Interrupting Capacity," *A.I.E.E. Trans.*, vol. 69, pp. 70–6, 1950. Disc., p. 76.

61. E. B. Rietz, "Development and Testing of an Improved High-Voltage High-Capacity Impulse Breaker," *A.I.E.E. Trans.*, vol. 69, pp. 15–52, 1950. Disc., p. 25.

E. Modernization of Oil Circuit Breakers

1. H. G. MacDonald, "Modern Performance from Old Breakers," *Elec. Jour.*, vol. 29, pp. 573–5, December, 1932.

2. R. E. Rowley, Jr., "Problems and Economies of Rebuilt Oil Switches," *Elec. West*, vol. 69, pp. 231–3, December 1, 1932.

3. C. C. McKee, "Decreased Operating Time Feature of Breaker Modernization," *Elec. West*, vol. 73, no. 3, pp. 32–3, September, 1934.

4. W. J. Lank, "Breakers Modernized with Minimum Ado," *Elec. Wld.*, vol. 105, p. 54 (2462), October 12, 1935.

5. J. H. Paget, "Modernized Breakers Cut Upkeep $5,000," *Elec. Wld.*, vol. 106, p. 78 (638), February 29, 1936.

6. J. H. Paget, "Rejuvenating Oil Circuit Breakers with De-ion Grids," *Elec. Jour.*, vol. 33, p. 362, August, 1936.

F. Magnetic Air Circuit Breakers

1. H. M. Wilcox, "Deion Circuit Breaker," *Elec. Jour.*, vol. 26, pp. 97–102, March, 1929.

2. J. Slepian, "Theory of the Deion Circuit-Breaker," *A.I.E.E. Trans.*, vol. 48, pp. 523–7, April, 1929. Disc., pp. 545–53.

3. R. C. Dickinson and B. P. Baker, "The Structural Development of the Deion Circuit-Breaker up to 15,000 Volts," *A.I.E.E. Trans.*, vol. 48, pp. 528–34, April, 1929. Disc., pp. 545–53.

4. B. G. Jamieson, "Field Tests of the Deion Circuit Breaker," *A.I.E.E. Trans.*, vol. 48, pp. 535–45, April, 1929. Disc., pp. 545–53.

5. R. C. Dickinson, "'De-ion' Air Circuit Breaker for A-C Feeder, Motor Starting, and Station Auxiliary Service," *A.I.E.E. Trans.*, vol. 57, pp. 649–53, November, 1938. Disc., pp. 653–6.

6. R. C. Dickinson, "High-Power 'De-ion' Air Circuit Breaker for Central-Station Service," *A.I.E.E. Trans.*, vol. 58, pp. 421–5, August, 1939. Disc., pp. 425–6.

7. E. W. Boehne and L. J. Linde, "'Magne-Blast' Air Circuit Breaker for 5,000-Volt Service," *A.I.E.E. Trans.*, vol. 59, pp. 202–8, April, 1940. Disc., pp. 208–12.

8. L. R. Ludwig and R. H. Nau, "Magnetic 'De-ion' Air Breaker for 2,500–5,000 Volts," *A.I.E.E. Trans.*, vol. 59, pp. 518–22, September, 1940. Disc., pp. 1125–9.

9. R. C. Dickinson and R. H. Nau, "A New Air Circuit Breaker with 250,000-Kva Interrupting Capacity," *A.I.E.E. Trans.*, vol. 60, pp. 197–201, May, 1941. Disc., pp. 671–2. De-ion.

10. R. C. Dickinson and B. I. Hayford, "A New 50,000-Kva 5-Kv Oilless Circuit-Breaker and Metal-Clad Switchgear Unit," *A.I.E.E. Trans.*, vol. 62, pp. 302–6, June, 1943. Disc., pp. 434–6. De-ion.

11. L. J. Linde and B. W. Wyman, "A Magnetic-Type Air Circuit Breaker for 15,000-Volt Services," *A.I.E.E. Trans.*, vol. 63, pp. 140–4, March, 1944. Disc., pp. 453–5. Magne-Blast.

12. R. C. Dickinson and Russell Frink, "Size Reduction and Rating Extension of Magnetic Air Circuit Breakers up to 500,000 Kva./15 Kv.," *A.I.E.E. Trans.*, vol. 65, pp. 220–3, April, 1946. Disc., pp. 510–1. De-ion.

13. L. J. Linde and B. W. Wyman, "The Development, Design, and Performance of Magnetic-Type Power Circuit Breakers," *A.I.E.E. Trans.*, vol. 65, 386–93, June, 1946. Disc., pp. 510–1. Magne-Blast.

14. See item A13*d*.

G. Air-Blast Circuit Breakers

1. J. Biermanns, "Hochleistungschalter ohne Öl (High-Capacity Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 50, pp. 1073–9, July 25, 1929; pp. 1114–9, August 1, 1929.

2. K. A. Wiedamann, "Aus der Entwicklung des Druckluftschalters (Development of Compressed-Air Circuit Breakers)," *E.T.Z.* (Berlin), vol. 50, pp. 1479–81, October 10, 1929.

3. J. Biermanns, "Hochleistungschalter ohne Öl (High-Capacity Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 51, pp. 299–304, February 27, 1930.

4. O. Mayr, "Die Weiterentwicklung des Druckgasschalters (The Further Development of the Compressed-Air Circuit Breaker)," *V.D.E. Fachberichte* (Berlin), vol. 5, pp. 45–7, 1931.

5. O. Mayr, "Latest Developments in Compressed-Gas Circuit-Breaker Design," *A.E.G. Progress* (Berlin), vol. 7, pp. 30–4, January-February, 1931.

6. O. Mayr, "Hochleistungschalter ohne Öl (High-Power Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 53, pp. 75–81, January 28, 1932; pp. 121–3, February 11, 1932.

7. Werner Uebermuth, "Die Entwicklung des Druckgasschalters zum wirtschaftlichen Gebrauchsschalter (The Development of the Compressed-Air Circuit Breakers into Practical Standard Form)," *V.D.I. Zeitschrift* (Berlin), vol. 77, pp. 40–4, January 14, 1933.

8. L. Haag and O. Schwenk, "Besondere Anwendung des Strömungsprinzips bei öllosen Leistungschaltern (Special Application of the Principles of Flow in Oilless Circuit Breakers)," *E.T.Z.* (Berlin), vol. 55, pp. 211–3, March 1, 1934.

9. O. Mayr, "Hochleistungschalter ohne Öl (High-Power Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 55, pp. 757–60, August 2, 1934; pp. 791–4, August 9, 1934; pp. 837–40, August 23, 1934. Disc., p. 849.

10. H. Thommen, "Die Entwicklung eines Druckluftschnellschalters (The Development of a Compressed-Air High-Speed Breaker)," *Schweizerischer Elektrotechnischer Verein* (*Association Suisse des Électriciens*) *Bull.* (Zurich), vol. 26, pp. 590–5, October 9, 1935.

11. W. Walty, "The Brown Boveri Air-Blast High-Speed Circuit Breaker," *Brown Boveri Rev.* (Baden), vol. 22, pp. 199–207, November, 1935.

12. F. Kesselring and F. Koppelmann, "Das Schaltproblem der Hochspannungstechnik (The Switching Problem in High-Voltage Engineering)," *Archiv für Elektrotechnik* (Berlin), vol. 30, pp. 71–108, 1936.

13. O. Schwenk, "Die Weiterentwicklung des Druckluftschalters mit doppeltwirkender Strömung (The Further Development of the Compressed-Air Breaker with Double-Acting Air Flow)," *V.D.E. Fachberichte* (Berlin), vol. 9, pp. 90–2, 1937.

14. J. Biermanns, "Fortschritte im Bau von Druckgasschaltern (Progress in

the Design of Compressed-Air Breakers)," *E.T.Z.* (Berlin), vol. 59, pp. 165–8, February 17, 1938; pp. 194–7, February 24, 1938.

15. F. PETERMICHL, "Ein kompressorloser Druckgasschalter (An Air-Blast Circuit Breaker without a Compressor)," *Elektrotechnik und Maschinenbau* (Vienna), vol. 56, pp. 286–9, May 29, 1938.

16. B. K. BOULTON, "Operating Experience with Air-Blast Circuit Breakers," *Elec. News and Eng.* (Toronto), vol. 47, no. 15, pp. 20–2 and 30, August 1, 1938.

17. Hs. THOMMEN, "The Further Development of the Air-Blast High-Speed Circuit Breaker up to the Highest Voltages Encountered in Service and for Outdoor Erection," *Brown Boveri Rev.* (Baden), vol. 26, pp. 55–68, March, 1939.

18. R. M. WILD and J. SCHNEIDER, "The Brown Boveri Air-Blast High-Speed Circuit Breaker and Its Importance for the Protection of Networks," *Brown Boveri Rev.* (Baden), vol. 26, pp. 106–11, April-May, 1939.

19. W. S. EDSALL, "A Typical European High-Speed Air Blast Circuit Breaker," *Allis-Chalmers Elec. Rev.*, vol. 4, no. 4, pp. 4–9, December, 1939.

20. "Air Blast Breakers Gain Acceptance," *Elec. Light and Power*, vol. 18, no. 4, pp. 48–58, April, 1940.

21. W. S. EDSALL and S. R. STUBBS, "Circuit Interruption by Air Blast," *A.I.E.E. Trans.*, vol. 59, pp. 503–9, September, 1940. Disc., pp. 1129–31.

22. D. C. PRINCE, J. A. HENLEY, and W. K. RANKIN, "The Cross-Air-Blast Circuit Breaker," *A.I.E.E. Trans.*, vol. 59, pp. 510–7, September, 1940. Disc., pp. 1121–3.

23. H. E. STRANG and A. C. BOISSEAU, "Design and Construction of High-Capacity Air-Blast Circuit Breakers," *A.I.E.E. Trans.*, vol. 59, pp. 522–7, September, 1940. Disc., p. 1131.

24. L. R. LUDWIG, H. L. RAWLINS, and B. P. BAKER, "A New 15-Kv Pneumatic Circuit Interrupter," *A.I.E.E. Trans.*, vol. 59, pp. 528–33, September, 1940. Disc., pp. 1123–5.

25. W. R. RANKIN and R. M. BENNETT, "A Conserved-Pressure Air-Blast Circuit Breaker for High-Voltage Service," *A.I.E.E. Trans.*, vol. 60, pp. 193–7, May, 1941. Disc., pp. 673–5.

26. L. R. LUDWIG and B. P. BAKER, "A Vertical-Flow Outdoor Compressed-Air Breaker," *A.I.E.E. Trans.*, vol. 60, pp. 217–22, May, 1941. Disc., pp. 672–3.

27. R. M. BENNETT and B. W. WYMAN, "Medium-Capacity Air-Blast Circuit Breakers for Metal-Clad Switchgear," *A.I.E.E. Trans.*, vol. 60, pp. 383–8, 1941. Disc., pp. 627–31.

28. H. W. HABERL and OTTO JENSEN, "Mechanical Simplicity of Air-Blast Circuit Breakers," *A.I.E.E. Trans.*, vol. 60, pp. 869–74, September, 1941. Disc., pp. 1355–6.

29. PHILIP SPORN and H. E. STRANG, "Field Tests and Performance of a High-Speed 138-Kv Air-Blast Circuit Breaker," *A.I.E.E. Trans.*, vol. 61, pp. 1–6, January, 1942. Disc., pp. 412–4.

30. H. D. BRALEY, "Field Tests on High-Capacity Station Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 31–5, January, 1942. Disc., pp. 408–9.

31. H. E. STRANG and W. F. SKEATS, "Field Tests on High-Capacity Air-Blast Station-Type Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 100–4, February, 1942. Disc., pp. 409–12.

32. L. R. LUDWIG, H. M. WILCOX, and B. P. BAKER, "A 2,500,000-Kva Compressed-Air Powerhouse Breaker," *A.I.E.E. Trans.*, vol. 61, pp. 235–41, May, 1942. Disc., pp. 414–7.

33. H. W. Haberl and R. A. Moore, "Some Air-Blast Circuit-Breaker Installations in Canada," *A.I.E.E. Trans.*, vol. 61, pp. 859–63. December, 1942. Disc., p. 1073.

34. Armin K. Leuthold, "Design and Operation of High-Voltage Axial Air-Blast Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 869–75, December, 1942. Disc., pp. 1073–4.

35. H. A. P. Langstaff and B. P. Baker, "A Vertical-Flow Compressed-Air Circuit Breaker and Its Application on a 132-Kv Power System," *A.I.E.E. Trans.*, vol. 62, pp. 188–92, April, 1943. Disc., pp. 436–7.

36. P. L. Taylor and H. W. Martin, "An Improved Axial Air-Blast Interrupter for Severe Operating Duty," *A.I.E.E. Trans.*, vol. 62, pp. 323–33, 1943. Disc., pp. 431–4.

37. H. L. Byrd and Ben S. Beall III, "A Three-Cycle 3,500-Megavolt-Ampere Air-Blast Circuit Breaker for 138,000-Volt Service," *A.I.E.E. Trans.*, vol. 64, pp. 229–32, May, 1945. Disc., pp. 463–71.

38. J. Labouret, "The Phenomenon of Retreat of the Electric Arc and the Thermodynamic Limit of the Rupturing Capacity of Air Circuit Breakers," *C.I.G.R.E.*, report 128, 1946.

39. Alexander Dovjikov and Clifford C. Diemond, "Performance Test of the Allgemeine Elektricitats Gesellschaft Free-Jet Air-Blast 220-Kv 2,500-Megavolt-Ampere Reclosing Circuit Breaker," *A.I.E.E. Trans.*, vol. 67, part I, pp. 295–304, 1948. Disc., pp. 304–6.

40. K. Ivar Lindström, "Air-Blast Circuit-Breakers for 220 kv and Higher Voltages for Swedish Networks," *C.I.G.R.E.*, report 105, 1948.

41. M. Poma, "Considerations on the Technique of Air-Blast Circuit-Breakers," *C.I.G.R.E.*, report 108, 1948.

42. F. Kurth, "Study of Problems in Circuit Interruption with Air-Blast Breakers," *C.I.G.R.E.*, report 128, 1948. Two resistance steps are advocated.

43. G. E. Jansson, "Large Indoor Power Air-Blast Circuit Breakers," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1675–8, 1948. Disc., p. 1679.

44. See item A13*e*.

45. B. P. Baker and E. Frisch, "A New 69-Kv Compressed-Air Circuit Breaker," *A.I.E.E. Trans.*, vol. 68, part I, pp. 363–8, 1949. Disc., pp. 369–72.

H. Water Circuit Breakers

1. J. Biermanns, "Hochleistungschalter ohne Öl (High-Capacity Circuit Breakers without Oil)," *E.T.Z.* (Berlin), vol. 51, pp. 299–304, February 27, 1930.

2. Fritz Kesselring, "Der Expansionsschalter (The Expansion Breaker)," *E.T.Z.* (Berlin), vol. 51, pp. 499–508, April 3, 1930.

3. Fritz Kesselring, "Die konstruktive Entwicklung des Expansionsschalters (The Development of the Designs of Expansion Circuit Breakers)," *Schweizerischer Elektrotechnischer Verein* (*Association Suisse des Électriciens*) *Bull.* (Zurich), vol. 22, pp. 254–60, May 27, 1931.

4. W. Kaufmann, "Neuere Versuchsergebnisse mit Expansionsschaltern (Recent Test Results with Expansion Breakers)," *V.D.E. Fachberichte* (Berlin), pp. 42–5, 1931.

5. W. F. Skeats and W. R. Saylor, "High-Capacity 'Hydro-Blast' Circuit Breaker for Central-Station Service," *A.I.E.E. Trans.*, vol. 59, pp. 111–4, February, 1940. Disc., pp. 114–6.

6. W. M. Leeds, "A High-Power Oilless Circuit Interrupter Using Water," *A.I.E.E. Trans.*, vol. 60, pp. 85–8, February, 1941. Disc., pp. 625–7.

7. J. Slepian, C. L. Denault, and A. P. Strom, "Dielectric Strength of Water in Relation to Use in Circuit Interrupters," *A.I.E.E. Trans.*, vol. 60, pp. 389–95, 1941. Disc., pp. 631–2.

I. Testing of Circuit Breakers

1. C. E. Merris, "The High Capacity Current Interrupting Testing Station of the General Electric Company," *Gen. Elec. Rev.*, vol. 26, pp. 455–9, June, 1923.

2. W. R. Woodward, "A High-Power Laboratory for Testing Oil Circuit Breakers and Other Apparatus," *Elec. Jour.*, vol. 23, pp. 102–6, March, 1926.

3. J. Biermanns, "Ölschalterversuche (Oil Circuit Breaker Tests)," *E.T.Z.* (Berlin), vol. 48, pp. 1137–43, August 11, 1927; pp. 1181–7, August 18, 1927.

4. J. Kopeliowitch, "Ölschalterversuche (Oil Circuit-Breaker Tests)," *E.T.Z.* (Berlin), vol. 49, pp. 676–81, May 3, 1928.

5. B. M. Jones and E. F. Zeigler, "Interrupting Capacity Testing of Large Oil Circuit Breakers," *Elec. Light and Power*, vol. 6, no. 12, pp. 26–9, 107–9, December, 1928.

6. C. J. Webb, "Testing High-Capacity Oil Switches—Some Details of a New French Installation," *Elec. Rev.* (London), vol. 105, pp. 383–5, September 6, 1929.

7. L. W. Dyer, "Field Tests on Deïon Grid Breakers," *Elec. Wld.*, vol. 95, pp. 786–92, April 19, 1930.

8. L. W. Dyer, "220-Kv. Tests on Deïon Grid Breakers," *Elec. Wld.*, vol. 95, pp. 844–8, April 26, 1930.

9. H. W. Clothier, "The Hebburn Short-Circuit Testing Plant," *Elec. Rev.* (London), vol. 106, pp. 996–1000, May 30, 1930.

10. D. F. Miner, "A Proving Ground for Circuit Breakers," *Elec. Jour.*, vol. 27, pp. 625–30, November, 1930.

11. M. W. Smith, "New 60,000-Kva. Generator for Testing Laboratory," *Power*, vol. 72, pp. 895–6, December 2, 1930.

12. W. R. Woodward and H. W. Tenny, "Westinghouse Increases Capacity of Its High Power Laboratory," *Power Plant Eng.*, vol. 35, pp. 268–9, February 15, 1931.

13. Philip Sporn and Harry P. St. Clair, "Oil Circuit Breaker Tests—Philo 1930," *A.I.E.E. Trans.*, vol. 50, pp. 498–505, June, 1931. Disc., pp. 521–31.

14. R. M. Spurck and H. E. Strang, "Circuit Breaker Field Tests on Standard and Oil-Blast Explosion-Chamber Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 50, pp. 513–21, June, 1931. Disc., pp. 521–31.

15. G. F. Davis, "High-Power Interrupting Capacity Testing Station of the General Electric Company," *Gen. Elec. Rev.*, vol. 35, pp. 99–106, February, 1932.

16. H. Thommen, "The Brown Boveri High Power Testing Plant," *Brown Boveri Rev.* (Baden), vol. 19, pp. 115–29, May-June, 1932.

17. R. M. Spurck and W. F. Skeats, "Interrupting Capacity Tests on Circuit Breakers," *A.I.E.E. Trans.*, vol. 52, pp. 832–40, September, 1933. Disc., pp. 840–3.

18. E. G. Ralston and E. H. Klemmer, "System Performance Tested with 600 Short Circuits," *Elec. Wld.*, vol. 101, pp. 192–5, February 11, 1933.

19. F. S. Douglass and A. C. Monteith, "Building a New Power System," *Elec. Jour.*, vol. 30, pp. 55–9, February, 1933.

20. A. W. Hill, "Testing a Power System," *Elec. Jour.*, vol. 30, pp. 95–7, 101, March, 1933.

21. P. O. Langguth and R. M. Smith, "What the Tests Show," *Elec. Jour.*, vol. 30, pp. 98–101, March, 1933.

References 18, 19, 20, and 21 are articles relating to tests on the power system of the Indianapolis Power and Light Company.

22. Wilfred F. Skeats, "Special Tests on Impulse Circuit Breakers," *Elec. Eng.*, vol. 55, pp. 710–7, June, 1936.

23. H. M. Wilcox, "Proving Tests for High-Voltage Breakers," *Elec. Wld.*, vol. 106, pp. 45–8 (3905–8), December 19, 1936.

24. Philip Sporn and H. P. St. Clair, "Tests on and Performance of a High-Speed Multibreak 138-Kv. Oil Circuit Breaker," *A.I.E.E. Trans.*, vol. 57, pp. 696–703, December, 1938. Disc., pp. 703–5.

25. H. J. Lingal, W. F. Skeats, and H. D. Braley, "Dielectric Strength of Oil for High-Voltage Testing of Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 60, pp. 903–6, September, 1941.

26. Philip Sporn and H. E. Strang, "Field Tests and Performance of a High-Speed 138-Kv Air-Blast Circuit Breaker," *A.I.E.E. Trans.*, vol. 61, pp. 1–6, January, 1942. Disc., pp. 412–4.

27. H. D. Braley, "Field Tests on High-Capacity Station Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 31–5, January, 1942. Disc., pp. 408–9.

28. J. B. MacNeill and W. B. Batten, "High-Capacity Circuit-Breaker Testing Station," *A.I.E.E. Trans.*, vol. 61, pp. 49–53, February, 1942. Disc., pp. 406–8.

29. H. E. Strang and W. F. Skeats, "Field Tests on High-Capacity Air-Blast Station-Type Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 100–4, February, 1942. Disc., pp. 409–12.

30. Philip Sporn and Harry P. St. Clair, "Field Tests and Performance of Heavy-Duty High-Speed 138-Kv Circuit Breakers—Oil and Air-Blast," *A.I.E.E. Trans.*, vol. 64, pp. 401–10, 1945. Disc., pp. 463–71.

31. W. B. Buchanan and G. D. Floyd, "Field Tests of Interrupting Capacity of 138-Kv. Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 65, pp. 199–204, April, 1946. Disc., pp. 503–4. Tests on 25-c.p.s. system of the Hydro-Electric Power Commission of Ontario.

32. W. H. Clagett and W. M. Leeds, "4,370,000-Kva. Short-Circuit Tests on Grand Coulee 230-Kv. Bus," *A.I.E.E. Trans.*, vol. 65, pp. 729–35, November, 1946. Disc., pp. 1119–21.

33. V. A. Brown, "The Short-Circuit Testing and Certification of High Power Electrical Apparatus," *C.I.G.R.E.*, report 138, 1946.

34. C. L. Killgore and W. H. Clagett, "Field Tests for Development of Ultra-high Interrupting Capacity 230 Kv. Oil Circuit Breakers," *C.I.G.R.E.*, report 130, 1948.

35. Ch. Bresson, "Indirect Tests on Circuit Breakers," *C.I.G.R.E.*, report 101, 1948.

36. E. Vogelsanger, "Indirect Circuit-Breaker Tests," *C.I.G.R.E.*, report 122, 1948. Contains bibliography with abstracts of 31 papers on this subject.

37. S. Teszner, A. Thibaudat, and F. Descans, "Direct and Indirect Tests on Circuit Breakers," *C.I.G.R.E.*, report 129, 1948.

38. A. Blaha, "Contribution to Indirect Tests of Circuit-Breakers," *C.I.G.R.E.*, report 132, 1948.

J. Mechanisms for Circuit Breakers

1. R. C. Cunningham and A. W. Hill, "A Compressed-Air Operating Mechanism for Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 695–8, September, 1942. Disc., pp. 1019–20.

2. L. J. Linde and E. B. Rietz, "A Pneumatic Mechanism for Outdoor Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 63, pp. 543–6, July, 1944. Disc., pp. 1428–9.

3. B. W. Wyman and J. H. Keagy, "New Solenoid Mechanism for Magne-Blast Breaker," *A.I.E.E. Trans.*, vol. 64, pp. 268–74, May, 1945. Disc., pp. 448–9.

4. W. A. McNeill, "Pneumatic Operation of Air Blast Circuit Breakers," *C.I.G.R.E.*, report 104, 1948.

5. B. W. Wyman and E. J. Casey, "A Manually Operated Spring Mechanism for Medium-Voltage Oilless Circuit Breakers," *A.I.E.E. Trans.*, vol. 68, part I, pp. 357–61, 1949. Disc., pp. 361–3.

K. Standards and Ratings

1. J. Kopeliowitsch, "Ueber die Notwendigkeit einer einheitlichen internationalen Definition der Abschaltleistung von Oelschaltern (On the Necessity of a Uniform International Definition of the Interrupting Capacity of Oil Circuit Breakers)," *Schweizerischer Elektrotechnischer Verein (Association Suisse des Électriciens) Bull.* (Zurich), vol. 19, pp. 277–91, May 1, 1928.

2. International Electrotechnical Commission, *Specification for Alternating-Current Circuit Breakers*, Publication 56, London, Gaylard and Son, 1937.

3. R. C. Van Sickle, "Power-Circuit-Breaker Ratings," *A.I.E.E. Trans.*, vol. 60, pp. 882–4, September, 1941. Disc., pp. 1353–5.

4. *Power Circuit Breaker Standards*, Publication 42–71, New York, National Electrical Manufacturers Association, 1942.*

5. *Oil Circuit Breakers*, A.I.E.E. Standards No. 19, New York, American Institute of Electrical Engineers, 1943.*

6. *American Standards for Alternating-Current Power Circuit Breakers*, New York, American Standards Association, 1945.* May be purchased from this Association at 70 East 45th Street, New York 17.

7. O. B. Vikoren, "Application Ratings of Indoor Power Circuit Breakers," *A.I.E.E. Trans.*, vol. 65, pp. 768–73, November, 1946. Disc., pp. 1168–70. Temperature rise due to normal current.

8. *American Standard Schedules of Preferred Ratings for Power Circuit Breakers*, Publication C37.6–1949, New York, American Standards Association, 1949.*

9. N.E.M.A. Standards, *Reclosing Duty Cycle Factors, Power Circuit Breakers*, revision of November 17, 1949 (mimeographed).* See Ref. 4.

L. Calculation of Fault Current for Circuit Breaker Application

1. W. M. Hanna, H. A. Travers, C. F. Wagner, C. A. Woodrow, and W. F. Skeats, "System Short-Circuit Currents—Proposed New Calculating Procedure for Application of Interrupting Devices and Relays," *A.I.E.E. Trans.*, vol. 60, pp. 877–81, September, 1941. Disc., pp. 1351–3.

2. A.I.E.E. Committee on Protective Devices, "Simplified Calculation of

*Since the standards of the A.I.E.E., A.S.A., and N.E.M.A. are revised from time to time, the latest editions should be consulted.

Fault Currents," *A.I.E.E. Trans.*, vol. 61, pp. 1133–5, 1942; also in *Elec. Eng.*, vol. 61, pp. 509–11, October, 1942.

3. A.I.E.E. Committee on Protective Devices, "Revisions Made to 'Simplified Calculation of Fault Currents,' " *Elec. Eng.*, vol. 63, p. 65, February, 1944.

4. A.I.E.E. Switchgear Committee, "Simplified Calculation of Fault Currents," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1433–5, 1948.

PROBLEMS ON CHAPTER VIII

1. Plot the ratio of rated interrupting capacity of a circuit breaker at system voltage to its rated interrupting capacity at rated voltage as a function of the ratio of system voltage to rated voltage. Do this for interrupting capacity (*a*) in kva. and (*b*) in amperes.

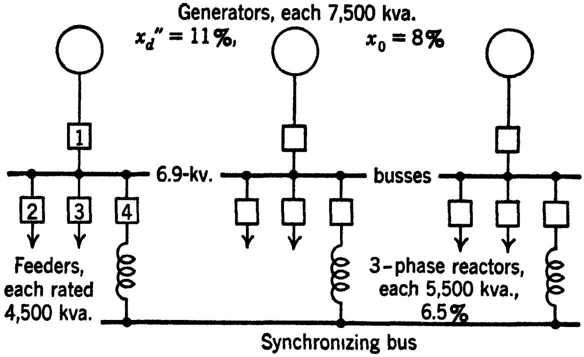

Generators, each 7,500 kva.
$x_d'' = 11\%$,
$x_0 = 8\%$
1
2
3
4
6.9-kv.
busses
Feeders, each rated 4,500 kva.
3-phase reactors, each 5,500 kva., 6.5%
Synchronizing bus

Fig. 31. Power system for illustrating circuit-breaker application (Probs. 2 to 5). Reactances are on the apparatus base.

2. Select from Table 1 a suitable oil circuit breaker for the feeders of the power system shown in Fig. 31. The neutral of each generator is solidly grounded.

3. Work Prob. 2 with all generators grounded through a common 4-ohm neutral resistor.

4. Work Prob. 2 with each generator grounded through a separate 0.1-ohm neutral reactor.

5. In the system of Fig. 31, would it be safe to use as circuit breaker 4 a breaker of the same rating as breakers 2 and 3?

(*The problems are continued on the next page.*)

6. Select from Table 3 a suitable air circuit breaker for the feeders of the power system of Fig. 32.

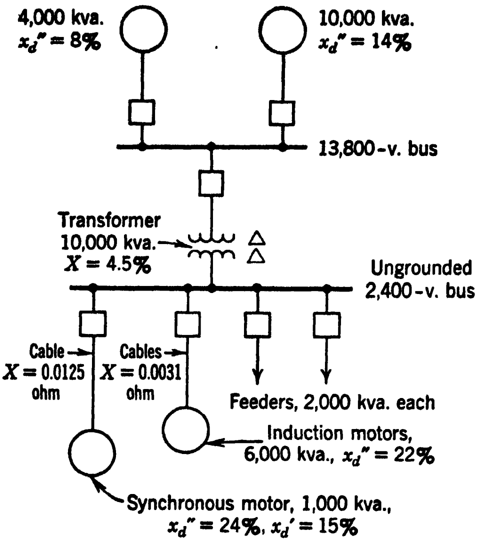


FIG. 32. Power system for illustrating circuit-breaker application (Prob. 6). Reactances are given on the apparatus base.

CHAPTER IX

FAULT CLEARING—PROTECTIVE RELAYS

General requirements. Circuit breakers alone do not suffice to clear faults: they must be supplemented by protective relays. The relays are required to detect the existence of faults and, if one does exist, to determine which breakers should be opened to clear it. Having determined the breakers to be opened, the relays should close the trip circuits of those breakers. No other breakers should be opened. This requirement is termed *selectivity.*

Selectivity will be illustrated by reference to Fig. 1, which shows a network divided into protective sections. When a fault occurs in any section, all the circuit breakers between that section and the adjacent sections should be tripped. For example, if a fault occurs at F, G, or H, breakers 4 and 5 should be opened. If a fault occurs on the bus at K, breakers 5, 6, and 12 should be opened. It is good practice to make the sections overlap at the breakers, as shown in the figure, so that a fault in or at a circuit breaker falls in both sections instead of in neither.

A second requirement of good relaying is *speed.* The advantages of high speed were discussed in Chapter VIII. When a fault occurs, the relays controlling any particular circuit breaker should be able to determine without delay whether the fault is inside or outside the section protected by those relays and that breaker. If the fault is inside the protected section, the relays should trip the breaker; otherwise, they should not. Unfortunately, the relays cannot always ascertain immediately whether a fault is internal or external. Then, since selectivity is more essential than speed, the relays must wait a while to see what other circuit breakers are going to do. The necessity for this wait is explained in the next section of this chapter.

A third requirement of relay schemes is usually that of providing *back-up protection* in the event that some other breaker should fail to open when it ought to. For example, if breaker 5 (Fig. 1) should fail to open for a fault at K, breaker 4 should be opened instead. The opening of the back-up breaker or breakers (no. 4 in this example) must be delayed long enough to give the proper breakers a chance to open first.

The various relay schemes, in use or proposed, should be examined

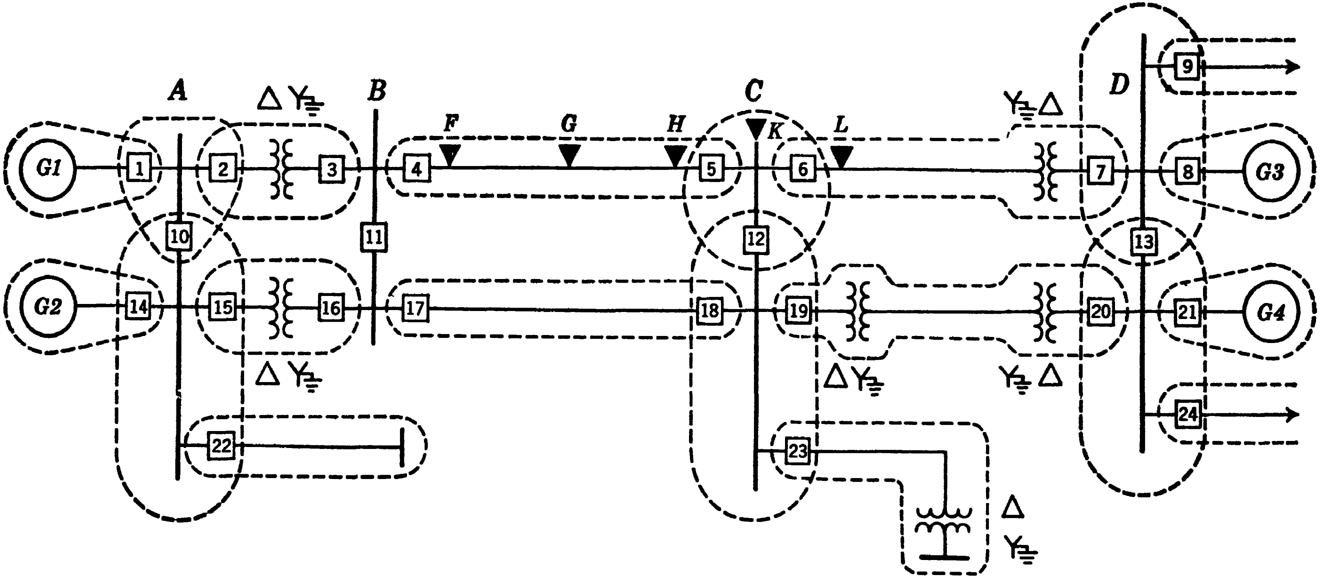


Fig. 1. A power network the protective relaying of which is considered in the text. The network is divided into overlapping protected sections, the boundaries of which are shown by broken lines. Some sections contain generators; others contain busses, transformers, transmission lines, or lines with transformers. Several possible fault locations are indicated by the symbol ▼.

to see how well they embody these three principles of selectivity, speed, and back-up protection.

In many relay schemes it is customary to use different relays for clearing one-line-to-ground faults from the relays for clearing faults involving two or more phase conductors (that is, line-to-line, two-line-to-ground, and three-phase faults). The two groups of relays are known as *ground relays* and *phase relays* (or *line relays*), respectively. The reasons for using separate relays will be explained in a subsequent section entitled "Ground-fault relaying." Most of the statements made below but before that section apply primarily to phase-fault relaying.

The relaying scheme adopted for any protected section will depend upon whether that section comprises a transmission line, a generator, a transformer bank, or a bus. Transmission-line protection will be considered first.

The problem of high-speed relay protection of transmission lines.^{B16} The relaying of transmission lines is important because the great majority of faults occurs on lines rather than on busses or apparatus. The greater vulnerability of lines arises from their length and their consequent exposure to lightning and to other hazards. High-speed relaying of lines is more difficult than high-speed relaying of other equipment because of the complication and expense of transmitting information from one terminal of the line to the other terminal, miles distant. In the absence of information transmitted from the distant end, the relays must depend upon local information to tell them whether to trip or not to trip; and this information is sometimes insufficient.

Reference to Fig. 1 may help to show why currents and voltages at one end of a line do not always suffice to tell whether a fault is in the protected section. The currents and voltages at circuit breaker 4 caused by a fault at *H*, just short of the far end of the protected section, are indistinguishable from those caused by a fault at *K* or *L*, just beyond the end of the section. Yet, for a fault at *H*, breaker 4 should be tripped; whereas, for a fault at *K* or *L*, it should not be tripped.

There are two methods of determining whether breaker 4 should be tripped for a fault near the far end. These methods are: (1) the transmittal of information from breaker 5 to breaker 4; and (2) the use of time delay. The second method does not fully satisfy the requirement of high-speed clearing.

Although from conditions at breaker 4 a fault at *H* cannot be distinguished from one at *K* or *L*, at breaker 5 the distinction is easily made. The currents in breaker 5 vary, especially in phase, according to which side of the breaker the fault is on. A fault at *H* causes power (or, more strictly speaking, volt-amperes at a lagging power factor dependent upon the angle of line impedance) to flow *into* the protected section; a fault at *K* or *L* causes power to flow *out* of the section. Therefore, a signal transmitted from breaker 5 to breaker 4 over a carrier-current channel, or other communication channel, can be used either to permit or to block tripping of breaker 4, according to the direction of current or power at breaker 5. This method of obtaining selectivity is known as *pilot relaying.*

The second method of distinguishing between internal and external faults near the far end is to delay the tripping of the breaker long enough to allow some other breaker to open first. With a fault at *H*, *K*, or *L*, for example, the tripping of breaker 4 is delayed. If the fault is at *L*, breaker 6 is tripped immediately. If the fault is on the bus at *K*, breakers 5, 6, and 12 are tripped immediately. In either event, as soon as these breakers have opened, conditions at breaker 4 change so as to indicate clearly that there is no fault in the protected section. Thereupon the relays at breaker 4 reset without tripping that breaker. If, however, the fault is at *H*, the opening of breaker 5, which is tripped immediately, does not greatly alter conditions at breaker 4. The indication of a fault near the distant end of the section persists, and, consequently, breaker 4 is tripped after the expiration of the time delay.

In the event that the proper breakers fail to clear a fault at *K* or *L* because of failure either of the relays or of the breakers, breaker 4, together with other breakers, provides time-delay back-up protection.

It is only for faults near the far end of a section that there is uncertainty regarding whether the fault is inside or outside the section. Thus, for a fault at *F*, breaker 4 is tripped immediately, but breaker 5 is delayed unless a pilot system is used. The roles of breakers 4 and 5 are exactly interchanged from what they were with a fault at *H*. For a fault at *G*, both breakers 4 and 5 are tripped instantly, even without a pilot system.

Kinds of time delay. The time delay—which, as has been shown, is required unless a pilot system is used—may be accomplished in any of several ways, which are best illustrated by means of diagrams of tripping time versus fault location (Fig. 2). The time delay may be constant, as shown in part *a*; it may increase continuously with increasing distance of the fault from the relay, as shown in *b*; or it may increase in steps, as shown in *c*. With any kind of delay, the

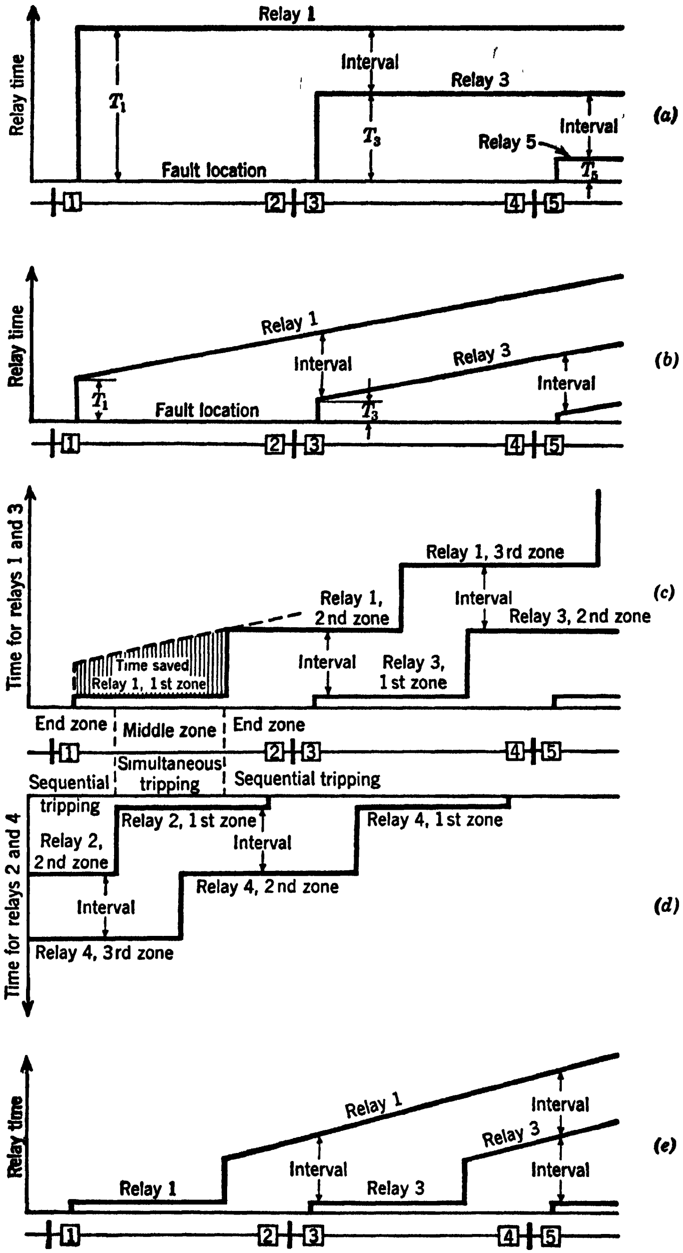


FIG. 2. Curves of relay time versus fault location. (*a*) Definite time. (*b*) Time increasing continuously with distance. (*c*) and (*d*) Time increasing in steps. (*e*) Combination characteristic.

same minimum time interval (marked "Interval" in Fig. 2) must be allowed between relays at successive sectionalizing points (such as breakers 1 and 3) for all fault locations that would actuate both relays. This interval should be the interrupting time of the breaker closer to the fault, plus a reasonable margin.

Upon comparison of curves *a*, *b*, and *c*, it is apparent that curve *b* represents a faster average relay speed than curve *a*; and *c*, a faster average speed than *b*. Curves *a* and *b* are typical of slow-speed relays; curve *c*, of high-speed relays. Curve *e* illustrates still another kind of high-speed-relay characteristic, a hybrid between the sloping characteristic *b* and the step characteristic *c*.

In Fig. 2*d* the tripping times of high-speed relays 2 and 4 are plotted below the horizontal axis, just as those of relays 1 and 3 are plotted above the axis in *c*. It may be observed from curves *c* and *d* that there is a zone near each end of the line in which faults are cleared by fast tripping of the breaker at the near end, followed by delayed tripping of the breaker at the far end. These zones are called *end zones*, and the manner of clearing faults therein is called *sequential tripping*. In the middle of the line, between the end zones, is a zone in which faults are cleared by simultaneous fast tripping of the breakers at both ends.

The various schemes of high-speed transmission-line relaying differ in the required lengths of the end zones and in the variation of their lengths with type of fault and with system conditions outside the protected section; but, unless a pilot channel is used, end-zone faults can be cleared only by sequential tripping. In pilot-relaying schemes, the end zones vanish.

Now that the general problem of relaying of transmission lines has been discussed, some of the common types of relay construction and some of the more important relaying schemes will be considered in greater detail.

Relay construction. Relays may be classified according to the type of construction (that is, the means by which current, voltage, or some function of currents and voltages is manifested in mechanical motion for opening or closing contacts) and according to the particular currents or voltages used. The three principal types of construction are: (1) induction disk, (2) induction cylinder, and (3) hinged armature or beam.

An *induction-disk relay* is similar in many respects to an induction watthour meter. It has a metal disk, the rotation of which opens or closes the relay contacts. The disk is acted upon by a driving magnet, between the poles of which the disk turns. The simplest driving magnet (Fig. 3) has one winding and a shading coil on the pole. The driving torque of such a magnet is proportional to the square of the current in the coil. Another kind of driving magnet (Fig. 4) is similar to that used in a watthour meter and has separate windings on the upper and lower poles. Its driving torque is proportional to $I_1 I_2 \sin \alpha$, where α is the phase difference between the currents I_1 and I_2 in the two windings.* In addition to the driving magnet, the disk is usually acted upon by a permanent magnet, which provides a braking torque proportional to the angular speed of the disk. Since the disk soon accelerates to a speed where the brake torque balances the driving torque, the disk turns at a speed proportional to the driving torque, and the operating time is inversely proportional to the driving torque.

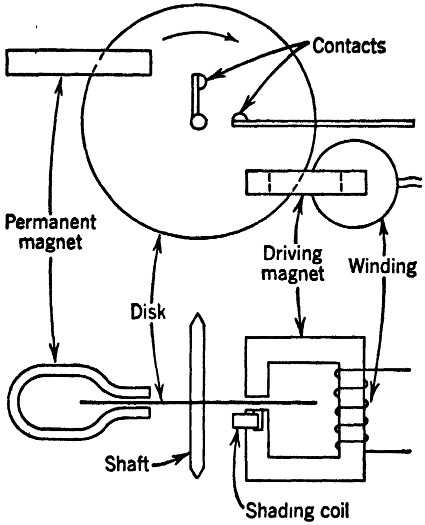


FIG. 3. Induction-disk relay with shaded-pole driving magnet.

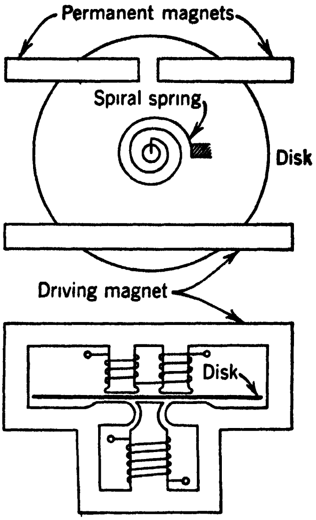


FIG. 4. Induction-disk relay with multipolar driving magnet.

---

*For example, a power relay can be obtained by making I_1 the same as current I of the protected circuit and having I_2 result from impressing the voltage V of the protected circuit on an inductive winding of negligible resistance, so that I_2 lags nearly 90° behind V. Then $\alpha = \phi - 90°$, where ϕ is the phase angle between V and I, and the torque is proportional to $VI \cos \phi$, or power, just as it is in a watthour meter. As another example, a current relay can be obtained by supplying I_2 from a secondary winding on the poles with the winding which carries I_1, so that I_2 is proportional to I_1 but differs in phase. The torque is then proportional to I_1^2.

Sometimes either a weight or a spring also acts on the rotating system to provide a more or less constant torque, or "bias." Then the disk does not turn at all until the driving torque overcomes the bias.

The induction-disk construction is used for slow-speed relays. In many such relays, the operating time is adjusted by changing the angle through which the disk must turn to actuate the contacts.

For high-speed relays the *induction-cylinder* construction (Fig. 5) is better than the induction disk because the moment of inertia can be made much smaller for the same driving torque. The moving element is a hollow metal cylinder or cup, which turns on its axis. The driving element consists of four or more poles placed radially around the outside of the cylinder and joined by an iron yoke. To shorten the air gap without increasing the inertia, a stationary iron core is placed inside the rotatable cylinder. Brake magnets are not used with the induction cylinder.

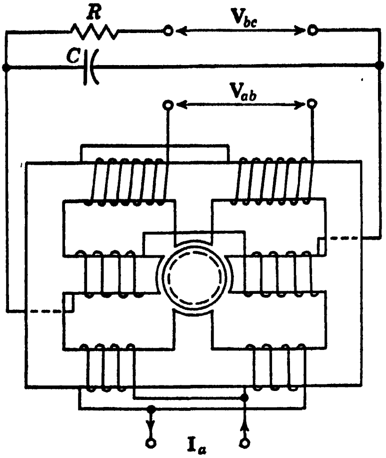


FIG. 5. Induction-cylinder relay (starting unit of old Type GCX relay).

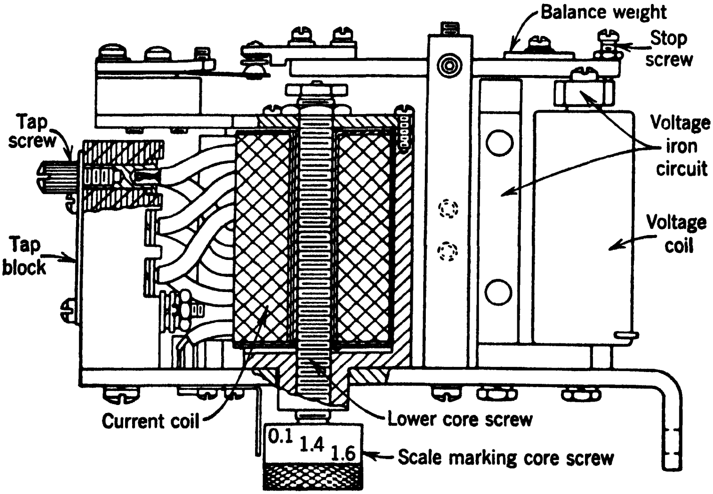


FIG. 6. Beam relay (Type HZ high-speed impedance relay, first-zone element). (By courtesy of Westinghouse Electric Corporation)

Still higher operating speeds can be attained with a *hinged armature or beam,* attracted by one or more electromagnets (Figs. 6 and 7). The pull of each electromagnet is proportional to the square of the current in its coil. In the beam type of relay element, two electromagnets act upon opposite ends of a beam. As in the induction relays, mechanical bias may be provided by gravity or by a spring.

Plunger, or *solenoid, relays* (Fig. 8) are used occasionally.

Vacuum or *gas-filled electron tubes*[L1-2] appear promising for protective relays, but they have been seldom used except in carrier-current relaying (discussed later in this chapter).

For further information on the construction of various types of relays, see the manufacturers' bulletins.[A1]

Relay currents and voltages. The action of any protective relay depends upon the currents and voltages supplied to it. The relay currents and voltages are taken, not directly from the protected circuit, but through instrument transformers. The transformers serve to reduce the currents and voltages to values for which the relays can be conveniently wound and to insulate the relays from high-voltage circuits. The relay currents are obtained from current transformers; the voltages, from either potential transformers or capacitance potential devices. Ordinarily three current transformers are used on each three-phase circuit, with the primary winding of each in series with one line wire and the three secondary windings connected in Y. Either three potential transformers are used, connected Y–Y with grounded neutrals, or two potential transformers, connected V–V. Three transformers are used if line-to-ground voltages are required; otherwise, only two are needed. One set of transformers, connected to a station bus, suffices to supply voltage to relays on all the circuits connected to that bus.

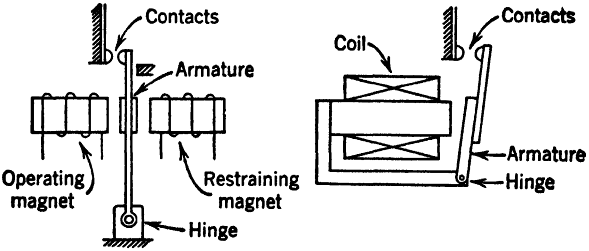


FIG. 7. Hinged-armature relays.

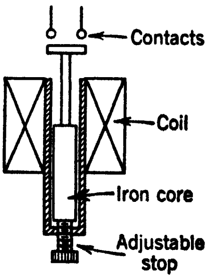


FIG. 8. Plunger relay.

The accuracy and reliability of some relaying schemes† depend greatly upon the accuracy of the instrument transformers, particularly on that of the current transformers when they are carrying the high currents which flow during short circuits. The accuracy of current transformers varies with the burden imposed by the relays and secondary wiring, as well as with the design of the transformer.

On high-voltage circuits (66 kv. and above) bushing current transformers, which are built into the bushings of the circuit breakers (as shown in Figs. 6 and 23 of Chapter VIII), are much cheaper than separate transformers, with their separate tanks and bushings. Bushing current transformers are therefore used extensively, despite the fact that their accuracy is lower than that of wound-primary transformers. Their accuracy is lowered by the small number of primary ampere-turns (the primary "winding" is a straight bar, equivalent to one turn), requiring a large component of primary current as exciting current. Capacitance potential devices[J3] built into circuit-breaker bushings often take the place of potential transformers on high-voltage circuits and effect a saving just as bushing current transformers do. These devices are essentially capacitance voltage dividers, consisting of a number of capacitors in series from the high-voltage circuit to ground, the secondary voltage being taken from the terminals of the capacitor next to ground.

The currents and voltages available for relay use are the three line currents and the three line-to-ground voltages of the protected circuit (and sometimes also those of neighboring circuits); also various linear combinations of these currents and voltages, such as the line-to-line voltages, which are differences of line-to-ground voltages; the "delta currents," which are differences of line currents; and the symmetrical components of voltage and current, especially the zero-sequence components. The relay action may depend upon a change in one of the said quantities, upon a change in the product or ratio of two of the quantities, or upon a change in some more complicated function of the quantities.

Overcurrent relaying. *Slow-speed relays.* The most obvious effect of a fault is to change the current in the faulted conductor from a normal value to an abnormally large one. Therefore it is not surprising that the earliest methods of clearing faults were based on the utilization of that effect (overcurrent). Early methods included fuses, circuit breakers with series trip coils, and slow-speed overcurrent relays.

---

†Discussed further under the headings "Apparatus protection" and "Bus protection."

Slow-speed overcurrent relays are mostly of the induction type (for example, Westinghouse Type CO and General Electric Type IAC).

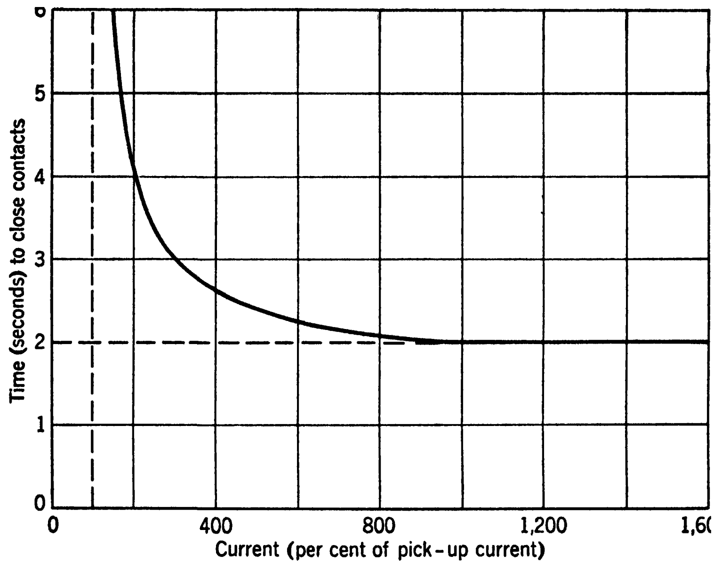


FIG. 9. Time-current characteristic of a slow-speed overcurrent relay (inverse with definite minimum) for a particular setting. Independent time and current settings are provided which alter the time and current scales, respectively, of the characteristic curve.

To obtain selectivity without unnecessarily long delay, such relays usually have a delay which varies inversely with the current, as shown in Fig. 9. Both time and current settings are adjustable. Since the fault current decreases, on account of the increased impedance of the line between the fault and the source, as the fault is moved farther from the source of power, it follows that the relay operating time increases as the distance to the fault increases. Hence the curve of relay time versus fault location is similar to curve *b* of Fig. 2, except that the sloping part of the curve may not be straight. The time-distance curves of relays 1 and 3 (Fig. 2*b*) should be separated by a time interval adequate for selectivity.

The time-distance curves change with such conditions as connected generating capacity and the connection or disconnection of other transmission lines; and, therefore, to ensure selectivity, curves should be checked for several conditions to ascertain that under the worst condition an adequate interval exists between the operating times of relays 1 and 3, and, similarly, between each pair of relays on adjoining line sections. Coordination may be accomplished by judicious choice of both time settings and current settings.

If the relay current changes but little with fault location, the curve of relay time versus fault position becomes more like curve *a*, Fig. 2, than like curve *b*. Such a condition is likely to exist if the impedance of the protected section is small compared to the impedance between the generators and the protected section, as may well be true if the section is short and is fed solely or principally from one end. Moreover, curve *a* may hold even though the relay current does change with fault location, if, as is usually true, the relays are operating on the minimum-time part of their time-current characteristic (Fig. 9). Curve *a* of Fig. 2 represents an undesirable condition when several protected line sections are in cascade, because the relay times of the lines near the source of power become increasingly long. For example, T_1 is considerably greater than T_3 (Fig. 2*a*).

If a line section is long or has power sources at each end, the relay current will vary considerably with fault location. But, even if the current varies enough to give a curve like *b*, Fig. 2, the operating time of a relay near the generator (T_1) is usually somewhat longer than that of a relay farther from the generator (T_3), though not so much longer as in curve *a*.

By the use of graded time settings, overcurrent relays can always be made to work selectively on a radial transmission or distribution system. With graded settings, and with the addition of directional relays (described in the next section of this chapter), overcurrent relays can be made to work selectively on a loop system fed from one point. But on a loop fed sometimes from one point and sometimes from another, or on a network more complex than a loop, it is difficult, if not impossible, to choose settings for overcurrent relays so that the relays will work selectively for all fault locations and for all operating conditions.

High-speed relays. It has already been noted that the relay current during a fault usually decreases as the distance to the fault increases. When the fault is exactly at the far end of the protected section, the relay current has a certain value, and, provided that other conditions are constant, a relay current exceeding this value is a certain indication of a fault in the protected section—a condition for which the circuit breaker should be tripped. Tripping may be accomplished under these conditions by the use of a high-speed overcurrent relay having a pick-up current equal to the current produced by a fault at the distant end of the section. In practice the *balance point* of the relay (that is, the fault location that will just make the relay pick up) must be somewhat closer than the distant end, for reasons already discussed. The contacts of the high-speed relay are connected in parallel with the contacts of a slow-speed overcurrent relay so that either relay can trip the circuit breaker. The combined tripping-time characteristic curve is then as shown in Fig. 2*e*. Faults closer to the relay location than the balance point of the high-speed relay are cleared by this relay. Clearing of faults farther away (that is, in the end zone) and back-up protection of the next section are accomplished by the slow-speed relay.

The chief weakness of high-speed overcurrent relaying is that the balance point varies with the type of fault and with conditions outside the protected section, such as the connected generating capacity and the opening or closing of other transmission lines. For example, a three-phase fault usually results in greater fault current than a line-to-line fault at the same place. Hence, in order to produce equal currents in an overcurrent relay, the three-phase fault must be farther from the relay than the line-to-line fault. In other words, the balance point for a three-phase fault is farther from the relay than is the balance point for a line-to-line fault. Again, the addition of generating capacity, or the closing of an additional transmission line, may decrease the impedance between the sources of power and the fault, thereby increasing the fault current for a given type and location of fault, or, in other words, shifting the balance point farther away from the relay. To assure selective relay action, the balance point must never be permitted to move out of the protected section under the most severe fault conditions. If the high-speed overcurrent relay is set so that this danger is avoided, then the balance point must shift a considerable distance toward the relay under less severe fault conditions, giving a long end zone, faults in which are cleared with delay, and a short—perhaps vanishing—zone in which faults are cleared rapidly. It is apparent that high-speed overcurrent relays cannot be depended upon to clear faults consistently over a large portion of the line unless external conditions are fairly constant. Nevertheless, the addition of a high-speed overcurrent relay to an existing slow-speed overcurrent-relay installation will effect more or less improvement in the average speed of clearing faults.

The connections of slow-speed and high-speed overcurrent relays for protecting a three-phase transmission line against phase faults are shown in Fig. 10. Two relays are used per phase, their current windings being in series. The trip contacts of all six relays are in parallel.

Directional relays. Except at locations where fault power can flow in only one direction, overcurrent relays must be supplemented by

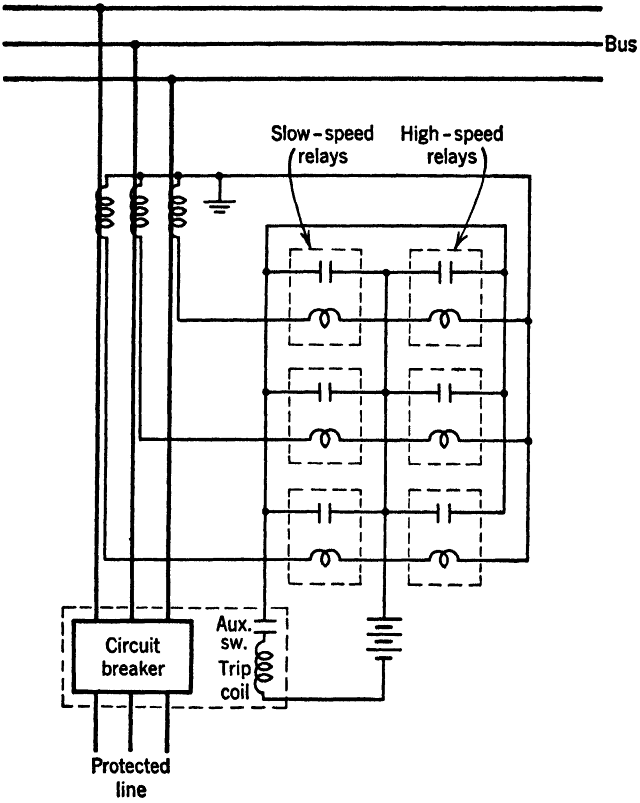


Fig. 10. Connections of slow-speed and high-speed overcurrent relays for protecting a three-phase transmission line against phase faults. The curve of relay time versus fault location resembles curve *e* of Fig. 2.

directional relays. Consider relay 5, Fig. 1. Faults on either side of this relay cause abnormally high currents to pass through it, actuating its overcurrent element. For a fault at the left of the relay, as at *F*, *G*, or *H*, the relay should trip its breaker, but for a fault at the right of the relay, as at *L*, it should not trip. Relay 6, on the contrary, should trip for a fault on the right, but not for one on the left. Directional relays (or directional relay elements) must be used to discriminate between faults for which a relay should trip and those for which it should not trip, according to the direction of fault power. The tripping direction is away from the bus.

At relay locations where fault power can flow in only one direction, as on radial feeders (for example, breakers 22 and 23, Fig. 1), directional relays are not necessary.

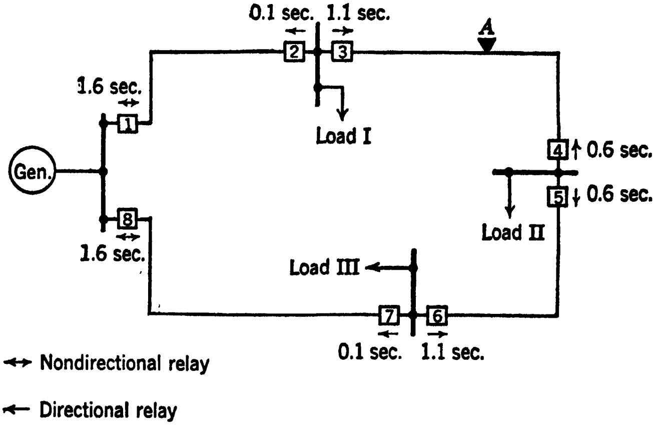


FIG. 11. Protection of a loop transmission circuit by directional overcurrent relays with graded time settings.

A directional relay is comparable to a contact-making wattmeter, except that it develops maximum torque not when the line current is in phase with the line-to-neutral voltage, but when it lags by an angle dependent upon the design and connections of the relay and chosen to approximate the angle of the impedance of the protected line. The torque acts to close contacts if the power (that is, the component of the volt-amperes at a certain lag angle) is flowing away from the bus, and to open the contacts if power is flowing toward the bus. These contacts are connected in series with the contacts of the associated overcurrent relay or relays, so that the trip circuit is completed only if there is both overcurrent and power flow away from the bus.

Protection of a loop transmission circuit by directional overcurrent relays is illustrated in Fig. 11. Selectivity is obtained by the use of directional elements and of graded time settings of the overcurrent elements. Suppose that a fault occurs at A. Current flows to the fault over two paths, one of which is through breakers 1, 2, and 3; the other, through breakers 8, 7, 6, 5, and 4. On the latter path, relays 5 and 7 are blocked by their directional elements. Of the remaining relays (8, 6, and 4), number 4 has the lowest time setting and trips its breaker, stopping flow of the fault current over the lower path and allowing the overcurrent elements of all the relays on this path to reset. On the upper path, relay 2 is blocked by its directional element, whereas relays 1 and 3 are free to trip. Relay 3, having a shorter time setting than relay 1, trips first, thereby completely isolating the fault from the system. In spite of the disconnection of line 3–4, no loads are interrupted: load I is supplied through breakers 1 and 2; loads II and III, through breakers 8, 7, 6, and 5. Relays 1 and 8 may be nondirectional, because fault power never flows toward the bus at the generating station, which is the only power source.‡

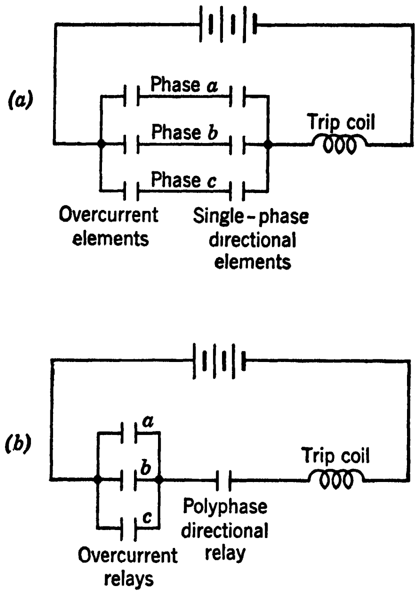


FIG. 12. Connections of contacts of directional overcurrent relays. (*a*) Three single-phase directional overcurrent relays, each consisting of an overcurrent element and a single-phase directional element. (*b*) Three overcurrent relays and one polyphase directional relay.

Directional relays may be either *single-phase* or *polyphase*. A polyphase directional relay consists either of three single-phase elements whose torques are added mechanically[C2] or of one polyphase element.[C1] A single-phase directional relay element is commonly combined with an overcurrent element to give a single-phase directional overcurrent relay (for example, Westinghouse Type CR). Three such relays are required to protect a three-phase circuit. Or, alternatively, one polyphase directional relay may be used in conjunction with three overcurrent relays to protect a three-phase circuit. Figure 12 shows the connections of the contacts for each of the two schemes.

Connections. Directional relays must be supplied with both current and voltage. The current and voltage windings can be connected to a three-phase circuit in a number of different ways. A common connection (known as the *90° connection*) is shown in Fig. 13. In this connection each directional element is supplied with a line-to-line voltage and with a line current which, under balanced unity-power-factor conditions, would lead the voltage by 90° (see Fig. 14). If the directional element had true wattmeter characteristics, it would

---

‡Relays 3 and 6 may also be nondirectional because the difference in time settings will make them select properly with relays 2 and 7 in case of a fault between either of them and the generating station.

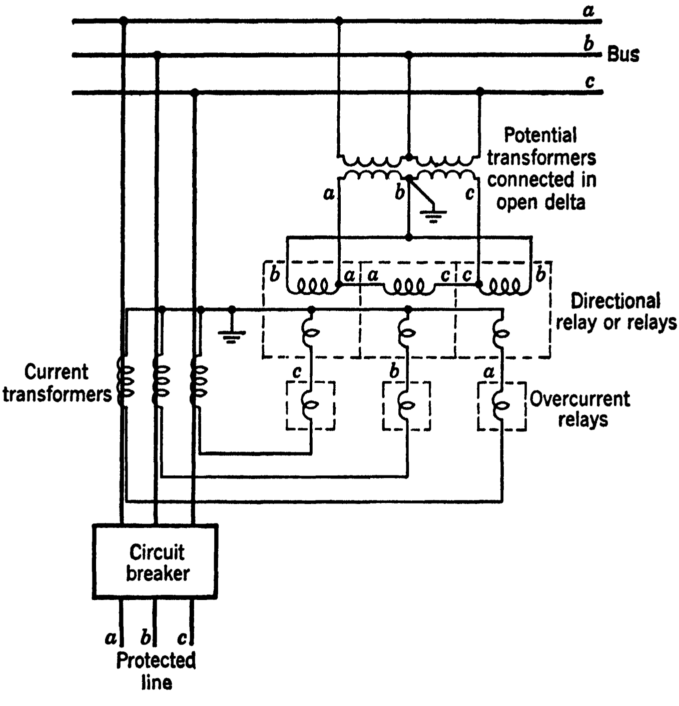


FIG. 13. The 90° connection of directional relays. (See Fig. 12 for trip circuit.)

develop maximum torque when the relay current was in phase with the relay voltage; that is, when the line current lagged 90° behind the corresponding line-to-neutral voltage under balanced conditions. However, by advancing the phase of the current in the highly inductive voltage winding through the use of a series resistor, maximum torque may be made to occur with the line current lagging the line-to-neutral voltage by a smaller angle, for example, 45°. Figure 15 illustrates the vector voltage and current relationships during a line-to-line fault. In this illustration all three single-phase directional elements would operate correctly, developing torque in the contact-closing direction. Reversal of the currents, due to shifting the fault to the other side of the relay location, would result in all three elements developing contact-opening torque. With the fault lying on the latter side, in the direction for which the relay should not trip, an incorrect closing

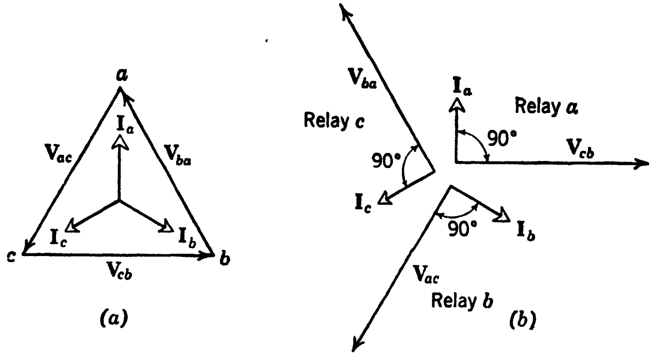


FIG. 14. (*a*) Vector diagram of line currents and line-to-line voltages for balanced unity-power-factor condition on a three-phase circuit. (*b*) The current and voltage of each directional-relay element in the 90° connection for the same condition.

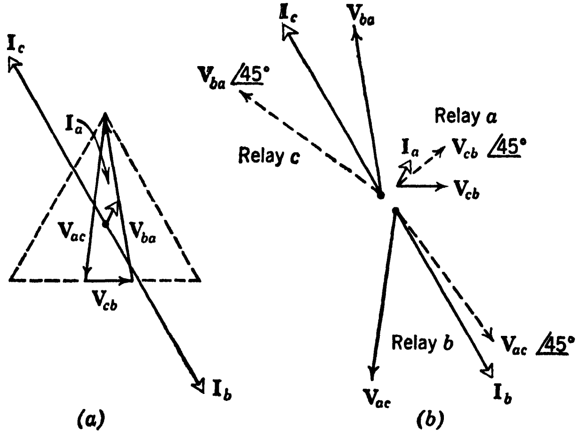


FIG. 15. (*a*) Vector diagram of voltages and currents at the relay location during a line-to-line fault on conductors *b* and *c* of the protected line. (*b*) The voltage and current of each directional-relay element under the same conditions. The voltage vectors drawn in broken lines are 45° ahead of the actual voltage vectors. The torque of each directional element is proportional to voltage × current × cosine of angle between current and advanced voltage. Under the assumed conditions, all three elements have contact-closing (tripping) torques.

torque in the directional elements of phase *b* or *c* would result in false tripping. However, a closing torque in the directional element of phase *a*, the unfaulted phase, would do no harm, because the contacts of the overcurrent element of this relay would be open and, being in series with the contacts of the directional element, would prevent tripping.

If a three-phase directional relay, instead of three single-phase relays, were supplied with the currents and voltages of Fig. 15, its torque would be correct also, because the torques of the individual elements—with the possible exception of the phase *a* element, whose torque is weak—are correct.

As further proof that the torque of a polyphase directional relay with the 90° connection is always correct, an expression will now be derived giving this torque in terms of symmetrical components of voltage and current. The torque of each element may be written as

$$T = KVI \cos (\phi - \psi) = K \operatorname{Re} (\bar{\mathbf{V}}\mathbf{I}\underline{/\psi}) \qquad [1]$$

where K is a constant, V is the voltage applied to the voltage winding of the relay element, I is the current in the current winding, ϕ is the angle by which V leads I, and ψ is the value of ϕ at which the relay has maximum closing torque. In an element having a true wattmeter characteristic, ψ would be zero. By the use of a resistor in series with the voltage winding, ψ may be given a negative value (commonly $-45°$), so that maximum torque occurs with leading current. The torque can be calculated either by use of the scalar values of V and I and the cosine or by taking the real part of the complex product of the complex current $\mathbf{I}$, the conjugate $\bar{\mathbf{V}}$ of the complex voltage $\mathbf{V}$, and the angle operator. The complex expression is the easier one to manipulate. The torque of a polyphase directional relay is the algebraic sum of the torques of the three single-phase elements.§ For the 90° connection, this torque is

$$T_3 = K \operatorname{Re} [(\bar{\mathbf{V}}_{cb}\mathbf{I}_a + \bar{\mathbf{V}}_{ac}\mathbf{I}_b + \bar{\mathbf{V}}_{ba}\mathbf{I}_c)\underline{/\psi}] \qquad [2]$$

Upon substitution of symmetrical components, this expression for torque becomes

$$T_3 = 3\sqrt{3}\, K \operatorname{Re} [(\bar{\mathbf{V}}_1\mathbf{I}_1 - \bar{\mathbf{V}}_2\mathbf{I}_2)\underline{/90° + \psi}] \qquad [3]$$

Here $\bar{\mathbf{V}}_1\mathbf{I}_1$ is the positive-sequence vector power, and $\bar{\mathbf{V}}_2\mathbf{I}_2$ is the negative-sequence vector power. The component of torque due to each sequence component of power is greatest if the current lags by an angle $90° + \psi$ behind the voltage. Thus, if $\psi = -45°$, maximum torque occurs at 45° lag, which is near the value of phase angle existing during a fault. Since positive-sequence fault power flows *toward* the fault, and negative-sequence power flows *away from* the fault, and since eq. 3 contains the *difference* of positive- and negative-sequence terms, it is clear that both positive- and negative-sequence fault powers produce torques of the correct sign. The only disturbing influence is the load component of positive-sequence power, which is usually negligible during phase faults.

---

§A single polyphase element gives a similar result (see Ref. C1).

Several other connections are used for some directional relays; especially the 30° connection, using line, or Y, currents and line-to-line, or Δ, voltages, such as I_a with V_{ca}; and the 60° connection, using Δ currents and Δ voltages, such as I_{ab} with V_{ac}. By and large, both these connections give correct operation of both single-phase and polyphase directional relays.[C3] However, single-phase directional overcurrent relays for phase-fault protection are likely to operate falsely if they use Y currents and Δ voltages and if the line on which they are installed carries much zero-sequence current and little positive- or negative-sequence current.

Sometimes the voltages of the low-voltage side of a bank of power transformers are used on a directional relay protecting a line connected to the high-voltage side of the bank. This is done to eliminate the need for expensive, high-voltage potential transformers.

Directional elements must operate correctly even though a three-phase fault close to the relays causes the applied voltage to become very low. Most directional elements will operate properly on 1% of normal voltage, and at least this amount is provided by arc drop in an arcing fault. In some high-speed relays the torque of the directional element under such conditions is improved by "memory action." That is, a resonant *L-C* circuit, formed by shunting the voltage winding of the relay with a capacitor, is used to retard the decay of voltage upon the occurrence of a fault.[C4] The *L-C* circuit is partially decoupled from the short-circuited line by a series resistor.

Directional control. Sometimes the direction of power in a sound line suddenly changes upon the complete or partial clearing of an external fault. Such power reversal could cause false tripping of slow-speed directional overcurrent relays on the sound line if means were not taken to prevent it. Two simple examples of possible false tripping will be given.[C4] Figure 16*a* illustrates a system where false tripping could occur upon clearing of a fault. Suppose that normal power flow at breaker 2 is in the direction of the arrow. When a fault occurs at *X*, the overcurrent element of relay 2 closes its contacts, but before it does so the directional element opens its contacts, thus preventing tripping. When the fault is cleared by breaker 1, the directional element of relay 2 quickly closes its contacts again, because it has full voltage and load current applied to it; but the overcurrent element, on the other hand, may open its contacts slowly if the load current is near the drop-out value of the element. If the directional contacts close before the overcurrent contacts have opened, breaker 2 will be tripped needlessly in spite of the fact that breaker 1 has already cleared the fault.

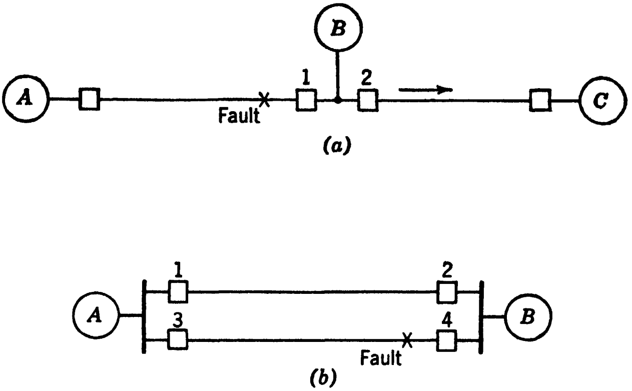


Fig. 16. Simple power systems in which false tripping of breaker 2 can occur upon clearing of an external fault if the directional overcurrent relays at breaker 2 do not have "directional control." (From Ref. C4 by permission)

Figure 16*b* illustrates a system layout where false relay operation could occur upon the partial clearing of a fault. If the generating capacity at A is greater than that at B, the overcurrent element at breaker 2 may operate for a fault at X, but tripping is prevented by the directional element. When breaker 4 opens to clear the fault partially, the power at breaker 2 reverses, and, as overcurrent still exists, the relay will trip breaker 2 unnecessarily.

The remedy is to allow the overcurrent element to operate and perform its timing function only while the directional element is in the tripping position. Then the overcurrent contacts will always be open when the directional contacts first close. This feature is known as *directional control.*

In high-speed directional overcurrent relays there are two problems of coordinating the contacts of the two elements to prevent false tripping.[C4] First, upon the occurrence of an external fault, the directional contacts must open before the overcurrent contacts close. This is no problem in a slow-speed relay, and it may be solved in a high-speed relay by introducing a short delay (about 1 cycle) in the operation of the overcurrent element. The situation is also aided by speeding up the opening of the directional contacts by use of a resonant circuit to sustain the voltage on the potential winding of the directional element. Second, upon the clearing of an external fault, either the overcurrent contacts must open before the directional contacts close, or else directional control of the overcurrent element must be exercised.

Distance relaying. *Slow-speed relays.* It is difficult or impossible to make slow-speed overcurrent relays work selectively on some system layouts because of the problem of choosing time settings which are correct under all conditions. Even when selectivity is achieved, the operating time of some of the relays is unnecessarily long. Both these shortcomings of overcurrent relays would be overcome if the operating time of each relay were made proportional to the distance from the relay to the fault, or—what amounts to the same thing—to the impedance between the relay and the fault. In the slow-speed induction-type impedance relay (such as Westinghouse Type CZ),[D1, 2, 3, 5] a disk turns at a speed proportional to the overcurrent, and the angle through which it must turn to close the tripping contacts is proportional to the voltage at the relay location. Hence the time required to close the contacts is proportional to voltage divided by overcurrent and therefore is nearly proportional to the impedance of the circuit from the relay to the fault. The time-position characteristic is that of curve *b*, Fig. 2, except that the minimum times T_1 and T_3 are equal. Directional elements must be used in conjunction with the impedance elements for the same reasons and under the same circumstances as with overcurrent relays.

High-speed distance relays. It has already been pointed out that the principal shortcoming of high-speed overcurrent relaying is the shifting of the balance point with type of fault and with such system operating conditions as connected generating capacity and the switching in or out of transmission lines or transformer banks. As a result of this shifting of the balance point, there are times when the zone of simultaneous high-speed tripping is greatly reduced in length or even vanishes altogether. High-speed distance relaying does not have this shortcoming: variation of the balance point with type of fault and system operating conditions is almost entirely eliminated. The term *distance relay* includes impedance relays, reactance relays, mho relays, modified mho and impedance relays, and combinations thereof. Of these, the impedance relay is the simplest and commonest and will therefore be discussed first.

Impedance relays. The high-speed impedance relay element closes its contacts immediately if the scalar value of impedance between the relay and the fault is less than the value for which the relay is set. Thus the balance point of the relay is at a distance from the relay equal to the impedance setting of the relay divided by the line impedance per unit length.|| The relay is supplied with the current and voltage of the protected line at the relay location. The impedance, as measured by the relay, is the ratio of voltage to current. A common form of the impedance relay (see Fig. 6, p. 74) consists of a balance beam controlling the contacts and acted upon by the pull of a current magnet at one end and by the pull of a voltage magnet at the other end.¶ The current magnet tends to close the contacts; the voltage magnet, to hold them open. With a fault at the balance point, the pulls of the two magnets are equal, and the beam is balanced. With a fault slightly closer to the relay than the balance point, the pull of the current magnet exceeds that of the voltage magnet, causing the contacts to close.

The balance point does not shift with change of generating capacity; for, if the generating capacity is reduced, the fault current and the relay current are decreased for a fault of constant type and location, but the relay voltage is also decreased in proportion to the current, because the voltage is equal to the relay current times the impedance of the line between the relay and the fault. The pull of the voltage magnet is reduced in the same ratio as that of the current magnet. Hence the beam balances at the same ratio of voltage to current, that is, at the same impedance as before.

The high-speed impedance element is usually set to balance for a fault distant between 80 and 90% of the whole length of the protected line, depending upon the judgment of the protection engineer. If the line impedance is determined by measurement, the higher value may be used; if it is determined by calculation, the lower value is safer.

Additional means are required to clear end-zone faults and to give back-up protection to the next section of line. A common kind of impedance relay (Westinghouse Type HZ)[D7] has three beam-type impedance elements, a directional element, and a timer. Each impedance element is set for a different value of impedance. The first element, as already stated, reaches out to 80 or 90% of the length of the protected section. The second element reaches to about 50% of the length of the next section. It serves to clear end-zone faults on the protected section and to give back-up protection to the nearer half of the next section. The third element reaches beyond the end

---

||Referred to the secondary side of the instrument transformers.

¶Actually, in order to reduce pulsation of the restraining force, two voltage magnets are used the currents of which are given a phase difference.

of the next section, thus giving back-up protection to the remainder of that section. The contact circuit is shown in Fig. 17. A directional element is included in the impedance relay for the reasons already stated in connection with the overcurrent relay. The trip circuit cannot be closed unless the contacts *D* of the directional element are closed.

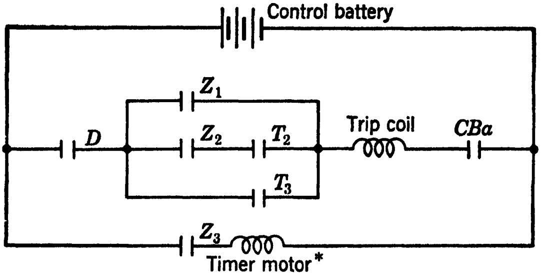


FIG. 17. Simplified contact circuit of Type HZ high-speed impedance relay.

D	Contacts of directional element.
Z_1	Contacts of first-zone impedance element.
Z_2	Contacts of second-zone impedance element.
Z_3	Contacts of third-zone impedance element.
T_2, T_3	Timer contacts.
CBa	Auxiliary switch on circuit breaker, used to open the trip circuit when the breaker opens.

* The timer motor actually operates on alternating current instead of on direct current as shown.

If these contacts are closed, the contacts Z_1 of the first or high-speed impedance element close the trip circuit directly, giving high-speed tripping. The contacts Z_2 of the second impedance element are in series with contacts T_2 of a timing element which is started by operation of the third impedance element Z_3. (This element, having the highest impedance setting, always operates when either of the other two impedance elements operates.) The timer, after lapse of a short time, closes contacts T_2, resulting in tripping if contacts Z_2 are closed even though Z_1 are not closed. Later, if contacts Z_3 remain closed, the timer closes contacts T_3, resulting in tripping even though neither Z_1 nor Z_2 are closed. The time settings of T_2 and T_3 are adjustable. The characteristic of tripping time of the complete relay is as shown in Fig. 2, curves *c* and *d*.

Another type of high-speed impedance relay (Westinghouse Type HCZ) has a high-speed impedance element combined with a slow-speed impedance element for end-zone and back-up protection.[D20] The tripping-time characteristic is as shown in Fig. 2, curve *e*.

There is one circumstance in which distance relays can be set to give instantaneous tripping for any fault location on the entire length of a transmission line, namely, when the line is terminated at the distant end in a transformer bank which is included in the same protective section as the line. The first-zone distance element may be set to reach beyond the end of the line into the transformer. It will operate for all line faults and for some, but not all, transformer faults. However, as line faults are considerably more frequent than transformer faults, the great majority of the faults on the section will be cleared at high speed. In Fig. 1, on the line between breakers 6 and 7, faults in the end zone near breaker 6 are cleared by sequential tripping of the breakers; all other line faults are cleared by simultaneous tripping. On the line between breakers 19 and 20, all line faults are cleared by simultaneous tripping without the use of a pilot channel.

Reactance relays. The impedance measured by an impedance relay includes the resistance of the arc at the fault. The arc resistance is negligible on high-voltage systems in comparison with the impedance between generator internal e.m.f. and the fault, and it is usually small in comparison with the impedance between relay location and a fault at the balance point, unless the line is short. Fault resistance varies with fault current and with the length of arc** (which may be lengthened by the wind), and, unless it is negligible, it will cause the balance point of an impedance relay to vary.

The reactance relay[D8, 16] was developed with the object of reducing the effect of fault resistance on the balance point. It consists of one or more reactance elements, a starting or fault-detecting element, a directional element (which may be combined with the starting element), and a timer.

**According to A. R. van C. Warrington[D25], arc resistance in ohms is approximately 8,750 $L/I^{1.4}$, where L is the length of arc in feet and I is the current in amperes. He recommends that, in considering the effect of arc resistance on distance relays, one should use the value 50 Kv/I for the instantaneous step and $50(Kv + 28vt)/I$ for the time steps. In these expressions, Kv is the nominal system voltage in kilovolts, I is the fault current in amperes, v, the wind velocity in miles per hour, and t, the time setting of the relay in seconds. For example, on a 110-kv. line with 10-ft. spacing, fault current of 700 amp., and wind velocity of 20 m.p.h., the arc resistance is initially about $8{,}750 \times 10/(700)^{1.4} = 9$ ohms by one formula, or $50 \times 110/700 = 8$ ohms by the other; after 0.5 sec. the resistance increases to approximately $50(110 + 28 \times 20 \times 0.5)/700 = 50 \times 390/700 = 28$ ohms. These values of resistance are equal to the reactance (per phase) of 10 and 35 miles, respectively, of line. They should be added vectorially to the line impedance to obtain the impedance presented to the relay. If the fault is fed from both ends, the apparent resistance of the fault is increased by the factor, fault current divided by current from near end.

Such a relay is the General Electric Type GCX high-speed reactance relay.[D37] The reactance element, or ohm unit, of this relay is a four-pole induction-cylinder element with windings arranged as shown in Fig. 18. The current windings produce flux in the front and back poles and in the right-hand side pole. The flux in the side pole is out of phase with that in the front and back poles because of the secondary winding, which is closed through a phase-shifting impedance, and the interaction of the two fluxes produces an operating torque, proportional to the square of the current, tending to close the relay contacts. The voltage winding on the left-hand side pole produces a flux which interacts with the flux of the front and back poles to produce a restraining torque (tending to open the contacts), proportional to the lagging reactive power, or to $VI \sin \phi$, where V is the relay voltage, I, the relay current, and ϕ, the angle by which V leads I. To operate the reactance element, the operating torque must exceed the restraining torque; thus[A12]

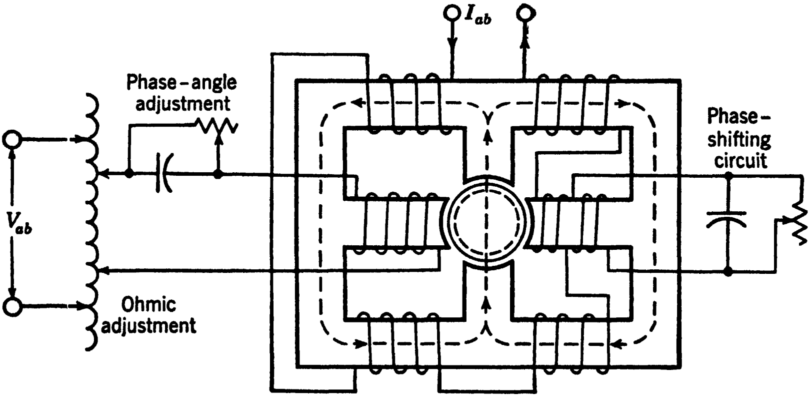


FIG. 18. Induction-cylinder reactance element (ohm unit) of Type GCX high-speed distance relay. The paths of the flux due to the main current winding are shown in broken lines. Actually the current winding is double, one part carrying I_a, the other $-I_b$, for reasons explained in the text under "Use of delta currents."

$$KI^2 > VI \sin \phi \tag{4}$$

$$K > \frac{V}{I} \sin \phi = Z \sin \phi = X \tag{5}$$

In other words, the reactance element operates if the reactance X measured by the relays is less than the setting K.

In the Type GCX relay, the reactance element does double duty, being used for both the first zone and the second zone. To accomplish this, the timing element, upon expiration of the second-zone time delay, actuates an auxiliary relay, whose contacts change the ohm setting of the reactance element to a higher value.

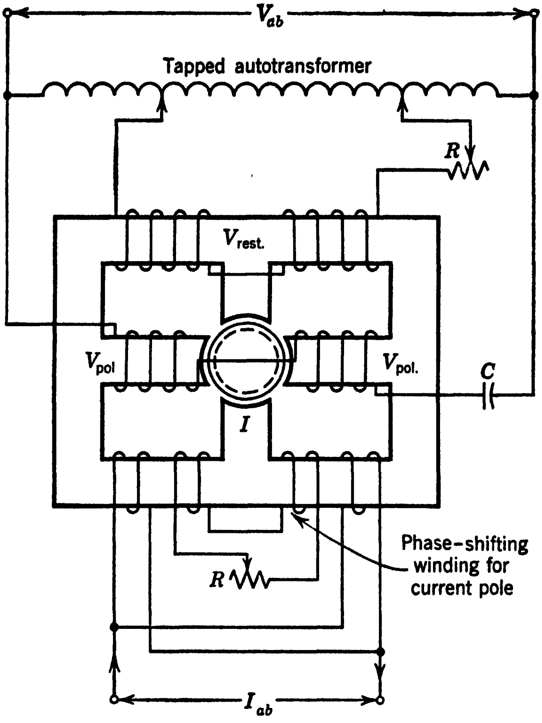


FIG. 19. Directional starting element (mho unit) of Type GCX high-speed distance relay.

Reactance elements of the beam type have been built also.[D7b, 22]

The reactance measured by the relay is the reactance of the line between the relay location and the fault, provided that the current in the fault is in phase with the relay current, as it usually is. If, on the other hand, the current in the fault is out of phase with the relay current, as it can be if the fault is fed from sources at both ends of the line the e.m.f.'s of which are out of phase, the fault resistance will appear as a positive or negative reactance, causing the balance point of the relay to shift one way or the other.

The reactance element alone is not sufficient to show the presence of a fault and should not be allowed to trip the breaker, for, under normal conditions with a load of high power factor. the measured reactance may be below the relay setting. To prevent false tripping under such conditions, the reactance element must be supervised by a fault-detecting element. Furthermore, a directional element is required for preventing tripping by an external fault behind the relay. In the Type GCX reactance relay, there is a directional starting element, which combines the functions of a directional element and of a fault-detecting element or third-zone distance element.

The directional starting element (Fig. 19) is similar in construction to the reactance element (Fig. 18) except for the placement and connections of the windings. The side poles are energized by voltage to produce the "polarizing" flux. The series capacitor provides "memory action." The front pole is energized by current, and the back pole by voltage. The directional starting element can be considered a directional element with voltage restraint. The torque of an unrestrained directional element, due to the current and polarizing voltage, would be $VI \cos (\phi - \psi)$, where V is the relay voltage, I is the relay current, ϕ is the angle by which V leads I, and ψ is the value of ϕ at which the relay develops maximum torque (adjustable by means of the resistance in the phase-shifting winding for the current pole). This torque, however, is opposed by the torque due to the two voltage windings and equal to KV^2, where K is a constant (adjustable by means of the tapped autotransformer). For operation of the starting element, the operating torque must exceed the restraining torque; that is,

$$VI \cos (\phi - \psi) > KV^2 \qquad [6]$$

$$\frac{I}{V} \cos (\phi - \psi) > K \qquad [7]$$

$$Y \cos (\phi - \psi) > K \qquad [8]$$

The last equation shows that the relay operates if the component of admittance Y at angle ψ exceeds the relay setting K.[A12] Angle ψ should be chosen near the line-impedance angle, making $\cos (\phi - \psi)$ nearly 1 during a fault in the tripping direction. Then the contacts will close if the admittance of the line between the relay and the fault is greater than the setting K.††

---

††Formerly, in the Type GCX relay, two different voltages, V_{ab} and V_{bc}, were used in the starting unit (see Fig. 5, p. 74). The operating torque was $V_{bc}I_a \cos (\alpha - 30°)$, where α is the angle by which I_a leads V_{bc}, and the restraining torque was $kV_{ab}V_{bc} \sin \beta$, where β is the angle between V_{ab} and V_{bc}. As a result, the "constants" K and ψ in eq. 8 varied somewhat with type of fault and with other system conditions, which determine β, and there was a consequent shift in the balance point, which was not as important in the third-zone element as in the first- and second-zone elements. See Prob. 9.

The *tripping characteristics of distance relays* may be shown advantageously by plotting the characteristics of each element in the complex impedance plane (Fig. 20). The characteristic of an impedance element is a circle with center at the origin (Z_1, Z_2, or Z_3, Fig. 20*a*). The contacts of the impedance element close for values of impedance *inside* the circle. The characteristic of a plain directional element is a straight line D through the origin and perpendicular to the angle line $O\psi$ drawn at the phase angle at which the element develops maximum torque. The contacts close for values of impedance above and to the right of the line. Since completion of the trip circuit requires closing the contacts of both an impedance element and the directional element, the tripping area (shaded in Fig. 20*a*) is inside the circle and above the straight line. For faults in the second and third zones, the timer contacts must close also. The areas marked T_1, T_2, T_3 correspond to different tripping times.

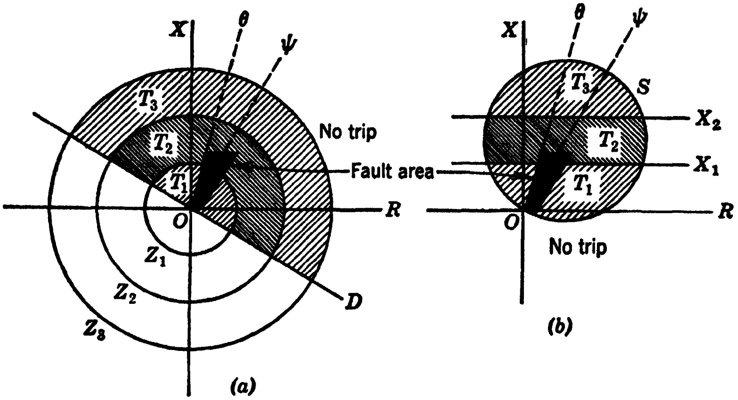


FIG. 20. Tripping characteristics of step-type distance relays plotted in the impedance ($R + jX$) plane. (*a*) Type HZ impedance relay. (*b*) Type GCX reactance relay.

Z_1, Z_2, Z_3	Impedance-element characteristics.
X_1, X_2	Reactance-element characteristics.
D	Directional-element characteristic.
S	Starting-element characteristic.
T_1, T_2, T_3	Shaded areas represent values of impedance for which relay closes the trip circuit instantaneously, with delay, and with more delay, respectively.
ψ	Angle of maximum torque of directional or starting element.
θ	Line-impedance angle. During metallic faults in the tripping direction, the impedance lies on $O\theta$.
Fault area	During arcing faults on the protected line, the impedance lies in this area.

The characteristic of a reactance element is a horizontal line (X_1 or X_2, Fig. 20*b*). The contacts close for values of impedance below the line. The characteristic of the directional starting element is a circle *S* passing through the origin and having a diameter on the angle line of maximum torque $O\psi$. The contacts close for values of impedance inside the circle. The tripping areas are marked as before.

The impedance "seen by" the relay on the faulted phase during an internal metallic short circuit lies on the angle line $O\theta$ corresponding to the line-impedance angle (preferably near line $O\psi$) and at a distance from the origin proportional to the distance to the fault. Arc resistance shifts the impedance to the right of line $O\theta$. Thus the impedance "seen" by the relays during a fault on the protected section lies in the solid-black area. During external faults in the nontripping direction, the impedance will lie in an area approximately 180° from that just described. The impedances seen during a fault by the relays on the unfaulted phases‡‡ and the impedances seen during normal-load conditions by all relays generally lie outside the tripping areas. During out-of-step conditions, or during large oscillations of the synchronous machines, the impedance may enter the tripping area. This possibility is discussed in Chapter X.

Mho relays.[D32, 33] The reactance element of a reactance relay is known also as an "ohm" element. Its characteristic curve in the impedance plane is a straight line. The directional starting element is known also as a "mho" element. Its characteristic in the admittance plane is a straight line; in the impedance plane this becomes a circle through the origin.

The General Electric Type GCY mho distance relay (Fig. 21) has a first-zone mho element M_1, a second-zone mho element M_2, and a third-zone offset mho element OM_3. No additional directional element is required because the mho elements are inherently directional.

The third-zone element, if its characteristic is offset as shown, gives back-up protection for external faults in both the forward and reverse directions. The amount of offset is adjustable and can be made zero if back-up protection for faults in the reverse direction is not required. The offset characteristic is obtained by adding to the line voltage a voltage proportional to the current and applying the sum to the relay coils.

A timing relay provides delays for the second and third zones. The complete mho relay has a step characteristic of time versus distance (Fig. 2*c*).

Induction-cylinder mho elements are said to have less transient overreach due to the d-c. component of fault current than beam-type impedance elements have.

---

‡‡Warrington[D40] gives a graphical method of finding these impedances.

The torque of a mho element becomes zero if the polarizing voltage becomes zero, as it may during a fault on or near the bus. By means of "memory action" (discussed previously under "Directional relays"), the polarizing voltage can be sustained a few cycles after occurrence of such a fault, long enough to operate the first-zone element but not the second- and third-zone elements with their associated time delays.

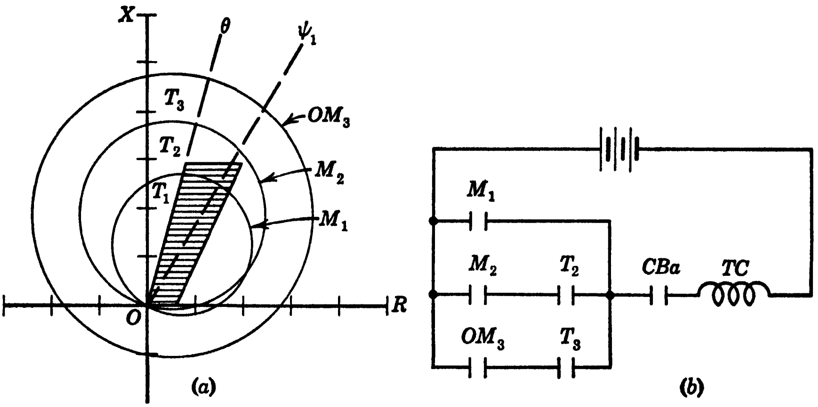


FIG. 21. Mho distance relay. (a) Tripping characteristics in the impedance plane. (b) Simplified diagram of trip circuit.

M_1	First-zone mho element.
M_2	Second-zone mho element.
OM_3	Third-zone offset mho element.
T_2, T_3	Timer relay.
TC	Trip coil of circuit breaker.
CBa	Auxiliary switch on circuit breaker.

The lines on which this relay is used must be long enough to provide sufficient voltage during a fault in the second zone.

Another application of the mho element is in association with a directional overcurrent time relay. The mho element clears first-zone faults instantaneously; the overcurrent relay clears second-zone faults and provides back-up protection. In order to permit the overcurrent relay to clear faults during times of minimum generation yet not to trip on load currents during times of maximum load, a second mho element is used to exercise directional control of the overcurrent element.

Modified impedance relays.[D12, 28, 30] The tripping characteristic of the ordinary impedance relay is a circle the center of which is at the origin of the impedance plane. The center of the circle may be shifted from the origin by adding to the voltage supplied to the restraining winding of the relay a voltage proportional to the line current. The resulting characteristic is like that of an offset mho element. The Westinghouse Type HZM relay is like the Type HZ impedance relay with the addition of external networks which afford adjustments of the direction and distance through which the center of the characteristic circle of each of the three beam elements is offset from the origin. The commonest form of network permits adjustment of the direction of the center from the origin through the range from 60° to 90°, and of the distance, from zero to 72% of the radius of the circle. Another form of network gives wider ranges: direction, 60° to 120°, and distance, zero to 100%.

The modified impedance relay was developed originally to have a characteristic approximating that of a reactance relay, with a balance point varying less with fault resistance than that of a plain impedance relay does.[D12] Such a characteristic, having a greater radius than that of the plain impedance relay with the same balance point, is needed mainly on short lines, where the arc resistance may be considerable in comparison with the impedance of the line.

At present, modified impedance relays and mho relays are used principally in order to obtain characteristics with smaller radii than those of plain impedance relays or reactance relays and thus to render the relays less likely to trip during heavy loads or during swings of the generators. For reasons that are discussed in Chapter X, such characteristics are needed principally on long lines.

Use of delta currents. In order for a high-speed distance relay to have its balance point independent of the type of fault, it must be supplied with suitable currents and voltages. When such relays were first introduced, they used line currents and line-to-line voltages. Lewis and Tippett[D9, 36] showed that the old connections gave a 15% difference between the indicated impedances of a line-to-line fault and of a three-phase fault at the same point of the line. They showed also that the use of "delta currents" (differences of two line currents) instead of line currents gave the same indicated impedance for line-to-line, two-line-to-ground, and three-phase faults at the same point; hence, the same balance point for these three faults. One of the three distance relays on a three-phase circuit should use the delta current $\mathbf{I}_c - \mathbf{I}_b$ together with the line-to-line ("delta") voltage $\mathbf{V}_c - \mathbf{V}_b$, where $\mathbf{V}_c$ and $\mathbf{V}_b$ denote line-to-ground voltages.

The fact that a relay using delta voltage and delta current "sees" the same impedance for any of three types of fault at the same location may be shown as follows:[A14] At a line-to-line or two-line-to-ground short circuit on wires *b* and *c*, the positive-sequence voltage is equal to the negative-sequence voltage. (Recall that the positive- and negative-sequence networks are connected in parallel, as shown in Vol. I, Chapter VI, Fig. 7.) Call the value of this voltage **V**. At a three-phase short circuit both these voltages are zero and therefore are again equal. At the relay location, the positive- and negative-sequence voltages are:

$$\mathbf{V}_1 = \mathbf{V} + \mathbf{Z}_1\mathbf{I}_1 \tag{9}$$

$$\mathbf{V}_2 = \mathbf{V} + \mathbf{Z}_1\mathbf{I}_2 \tag{10}$$

where $\mathbf{Z}_1$ is the positive-sequence impedance of the line between the relay and the fault (the negative-sequence impedance of the line has the same value), and $\mathbf{I}_1$ and $\mathbf{I}_2$ are the positive- and negative-sequence currents, respectively, flowing from relay to fault. The difference of eqs. 9 and 10 is

$$\mathbf{V}_1 - \mathbf{V}_2 = \mathbf{Z}_1(\mathbf{I}_1 - \mathbf{I}_2)$$

whence

$$\mathbf{Z}_1 = \frac{\mathbf{V}_1 - \mathbf{V}_2}{\mathbf{I}_1 - \mathbf{I}_2} \tag{11}$$

The impedance "seen" by the relay on the faulted phase has this same value, for it may be readily shown that

$$\frac{\mathbf{V}_c - \mathbf{V}_b}{\mathbf{I}_c - \mathbf{I}_b} = \frac{\mathbf{V}_1 - \mathbf{V}_2}{\mathbf{I}_1 - \mathbf{I}_2} \tag{12}$$

For all three types of fault, therefore, this impedance is the positive-sequence impedance $\mathbf{Z}_1$ between relay and fault. The impedance seen during a line-to-ground fault at the same location is higher than $\mathbf{Z}_1$, because the line-to-line voltage does not become zero at the fault.

The use of delta currents with distance relays is now standard practice. Delta currents may be obtained in several ways: by the use of Δ-connected secondary windings of the main current transformers or of auxiliary current transformers, or by the use of double windings on the current magnets of the impedance elements.

Constancy of the balance point is most important for the first-zone distance elements, so that the balance point can be set as close as possible to the far end of the protected line. The second- and third-zone balance points are subject to shift with variation in the amount of feed to the far-end bus from other sources than the protected line.

Balanced-current relaying of parallel lines. If two or more transmission lines of equal impedance run between the same two station busses and have no tapped loads, the lines carry equal currents both during normal conditions and during external faults. During a fault on one of the parallel lines, however, the faulted line carries more current than the sound line or lines. This fact is the basis of balanced-current relaying. In this scheme a relay responding to the difference of the currents in the corresponding phase conductors of two parallel lines is arranged to trip the line carrying the greater current. The difference may be arithmetical or vector, absolute or percentage, depending on the exact type of relay used.

Balanced-current relaying might be applied to the two parallel lines between busses *B* and *C* of the system of Fig. 1. The currents at points 4 and 17 near bus *B* are equal during external faults at *K* or *L*, but for internal faults at *F* or *G* current 4 exceeds current 17 and would cause a balanced-current relay to trip breaker 4. As the fault location is moved toward bus *C*, the difference of the currents in the two lines decreases, finally becoming zero as the fault reaches the bus. Thus a fault at *H* would not give a perceptible difference of current and would not actuate a current-balance relay at *B*. Indeed, there is a zone adjacent to bus *C*, the length of which is perhaps 10% of the length of the line, in which a fault would give too small a difference of current at *B* to actuate the relay there, unless the relay were given so sensitive a setting that there would be danger of its responding to external faults on account of slight differences in the characteristics of the current transformers, small differences in the impedances of the two lines, or other secondary factors. Thus current-balance relays have exactly the same limitation as distance relays in their inability to trip instantly the breakers of a faulted line for all fault locations. There is a zone at each end of the line in which faults are cleared sequentially.

Current-balance relaying has some advantage over distance relaying, however, in that end-zone faults are cleared with less delay. The way in which end-zone faults are cleared will be described for a fault at *H* (Fig. 1). This fault produces no unbalance between currents 4 and 17 at *B*, but it does produce an unbalance between currents 5 and 18 at *C*, causing high-speed tripping of breaker 5. As soon as breaker 5 opens, the current at 17 immediately decreases, producing an unbalance between currents 4 and 17, which causes breaker 4 to be tripped. The total clearing time of an end-zone fault is relay time plus breaker time at the near end plus relay time plus breaker time at the far end. In current-balance relaying the required time delay is obtained automatically and is always the minimum value consistent with selective operation, whereas, in distance relaying a "margin" must be added to allow for variation of breaker speed or timing-relay speed. With 1-cycle relays and 8-cycle breakers, the clearing time of end-zone faults would be 18 cycles for balanced-current relaying as against perhaps 28 cycles for distance relaying.

Although current-balance relays are made in both slow-speed and high-speed types, there is little need for time delay except the danger of occasional false trippings due to differences in residual magnetism in the current transformers. A very short delay suffices to prevent trouble from this cause.[J18]

As balanced-current relays are not affected by external faults, they need not be coordinated with the relays of adjacent line sections. For the same reason, they do not provide back-up protection of adjacent sections. Furthermore, they are not operative after one of two parallel lines has been switched out, and cannot be used on single circuits. Therefore, balanced-current relaying must be regarded merely as supplementary to some other kind of relaying, such as distance relaying, which will provide single-line protection and back-up protection.

Ground-fault relaying. The schemes of overcurrent and distance relaying which have been described in earlier sections of this chapter are intended primarily for clearing faults involving more than one line conductor. Usually, though not always, separate relays are provided for clearing one-line-to-ground faults. The reasons for this practice and the schemes used for ground-fault relaying will now be discussed, first, in connection with overcurrent relaying and, second, in connection with distance relaying.

Overcurrent relaying. The overcurrent relays provided for phase-fault protection generally respond to ground faults also, and on some circuits no other ground-fault protection is provided. However, the phase overcurrent relays must be given a setting high enough so that they do not respond to normal load currents or even to reasonable overloads, and under some conditions the currents flowing in the phase relays during ground faults may be less than the pick-up current of the relays. There are two reasons why ground-fault currents may be small. First, some transmission systems have neutrals grounded through high resistance or reactance for the purpose of limiting the ground-fault current and thereby decreasing the effect of one-line-to-ground faults (the most frequent type of fault) on voltage dip, conductor burning, telephone interference, and system stability. Second, even on systems grounded solidly or through low impedance, the ground-fault current may occasionally be limited to a small value by the resistance of the fault itself. Although the resistance of faults between two or more phase conductors is low, the resistance of faults from a conductor to ground may be high; for, in addition to the resistance of the arc, the resistance of a ground fault may include the grounding resistance of one or more poles or towers at the point of fault or, in extreme cases, the contact resistance of a conductor to ground or to some foreign grounded object. Even when the fault current is low and its effect on voltage and stability is correspondingly small, high-resistance ground faults, if due to a broken conductor on the ground or to contact of a foreign object with the line, represent a condition hazardous to life and property. Consequently, high-resistance ground faults must be cleared.

Relays for clearing ground faults operate, as a rule, on zero-sequence current or on zero-sequence current and voltage. Since zero-sequence quantities are absent under normal conditions, relays operating on such quantities can be set to trip the breaker for fault current lower than normal load current yet not to trip on heavy load current.

Both ground relays and phase relays respond to two-line-to-ground faults.

The connections of a directional overcurrent ground relay are shown in Fig. 22. Zero-sequence current for the overcurrent element and for the current winding of the directional element is obtained from the neutral conductor of Y-connected secondary windings of current transformers in the protected circuit. Zero-sequence voltage for the directional element is obtained from three bus potential transformers the primary windings of which are connected in Y and the secondary windings, in series (also called "broken delta").§§ Note that three potential transformers are required for the ground relay, whereas only two are needed for the phase relays. If there is a grounded-neutral power transformer on the bus, the neutral current of this transformer is proportional to the zero-sequence bus voltage and may be used instead of the zero-sequence voltage to polarize the directional element. During a ground fault on the protected circuit, zero-sequence power flows away from the fault and toward the bus; hence the directional element should close its contacts only when zero-sequence power flows toward the bus.

The use of a zero-sequence ground relay is advantageous because, as already stated, it can clear high-resistance ground faults which would not actuate the phase relays. Yet, even for ground faults which do produce a current great enough to operate the phase relays, a separate ground relay with its sensitive setting may result in faster clearing of ground faults than would otherwise be possible and thus may give improved protection.

---

§§In practice, the main potential transformers are connected Y–Y, so that secondary line-to-line voltages are available for phase relays and measuring instruments; and auxiliary low-voltage potential transformers, connected Y-series, are used for the ground relays.

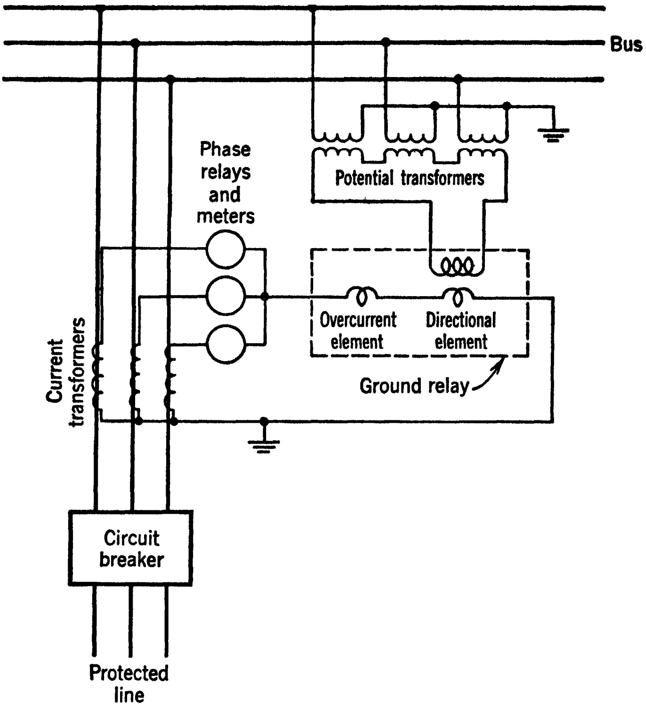


Fig. 22. Connections of the current and voltage circuits of a directional overcurrent ground relay.

Selectivity between different overcurrent ground relays on the same system is obtained by the same means that are employed with overcurrent phase relays, namely, by directional elements and by selective timing. In two respects, however, selectivity is more readily attained for ground relays than for phase relays:

1. Most transformer banks do not pass zero-sequence power; hence such banks sectionalize the power system into parts which are independent as regards ground relaying. Thus the number of relays which must be coordinated with one another is often less for

ground relays than for phase relays. As an extreme instance of such sectionalization, a transmission line with transformers at each end (such as line 19–20 of Fig. 1) may be operated and relayed as a single section. Any zero-sequence current on that line—with a few possible exceptions‖‖—indicates a ground fault on the line. Consequently, instantaneous nondirectional overcurrent ground relays at both ends of the line may be used to clear such faults. Neither directional elements nor time delay is needed to prevent false tripping during external faults.

2. On some systems the attainment of selectivity between ground relays is facilitated by the presence of many grounding points. Zero-sequence power originating from a fault on such a system flows principally to the nearest grounding point or points, with the result that the current in any particular relay varies rapidly with fault location. Curves of relay time versus fault position for such a system are similar to curve *b*, Fig. 2. High-speed overcurrent elements may be used advantageously on such a system to supplement the slow-speed relays.

Far different is a system grounded through high impedance and at only one grounding point. Here the total fault current is almost independent of fault location, and, therefore, selectivity must be obtained principally by graded time settings.

Although, as a rule, it is easier to secure selective operation of ground relays than of phase relays, ground relays are occasionally subject to trouble from which phase relays are free. Zero-sequence mutual impedance between parallel overhead transmission lines is appreciable, though positive- and negative-sequence mutual impedance is negligible. Consequently, zero-sequence current and voltage may be induced in a closed loop of a network by zero-sequence current in an adjacent faulted line, even a line of different voltage or frequency, thus causing false operation of ground relays.[E5, 8, 9]

Negative-sequence directional elements.[E4] Both zero-sequence power and negative-sequence power flow away from a fault. Therefore it is possible to use negative-sequence power instead of the customary zero-sequence power to operate the directional element of a ground relay, even though the overcurrent element is operated by zero-sequence current. Only two potential transformers are required instead of three, but filter networks must be used to obtain the required negative-sequence current and voltage. Although negative-sequence current could be used for the overcurrent element, as well as for the directional element, there is seldom, if ever, any advantage in doing so; it would only increase the burden on the current filter.

‖‖Zero-sequence current in line 19–20 could be caused by mutual induction from zero-sequence current on the parallel circuit 6–7. False tripping from this cause can be avoided by the use of a high enough current setting. It is also possible that high-speed ground relays may occasionally operate incorrectly during phase faults because of the effect of unequal residual magnetism in the current-transformer cores. A short time delay suffices to prevent incorrect operation from this cause.[J18]

Current-voltage-product relaying. Slow-speed impedance relays for phase-fault relaying may be regarded as slow-speed overcurrent relays modified so that they have time settings proportional to the voltage. As the voltage is low near the fault and increases with distance from it, the result is comparatively rapid operation of relays near the fault and slower operation of relays farther from the fault. When an attempt is made to apply this same principle to zero-sequence ground relaying, it is soon found that there is this difference: the zero-sequence voltage is greatest at the fault location and decreases with distance from the fault. Therefore, a ground relay operating on zero-sequence current and voltage should have a time setting which varies *inversely* instead of *directly* as the voltage. When this requirement is combined with the inverse current-time characteristic, it is clear that the relay should have a time delay which varies inversely as the product of voltage and current; that is, the relay speed should vary directly as this product. Thus the current-voltage-product ground relay is seen to be analogous to the slow-speed impedance phase relay.

The disk of the induction-type product relay rotates at a speed proportional to the product of voltage, current, and the cosine of the difference between the power-factor angle and the angle of maximum torque, or to $VI \cos (\phi - \psi)$. In other words, the speed is proportional to the component of vector power at a particular phase angle (usually near the line-impedance angle).

Because this relay is inherently directional, no directional element need be added to it.

At busses which have grounded-neutral power transformer banks, the neutral current of the bank may be used instead of the zero-sequence voltage, as explained above in connection with directional overcurrent ground relays.

High-speed distance relaying.[E3] It has already been noted that for high-speed clearing of phase faults, distance relays are superior to overcurrent relays because of the much smaller shift of the balance point of the former. It is only natural to try to gain the same advantage in clearing ground faults by high-speed distance ground relays. Zero-sequence current and voltage, though commonly used for ground relays of other types, are not suitable for distance ground relays; for, because of the fact that zero-sequence power flows away from the fault, the ratio of zero-sequence voltage at the relay location to zero-sequence current at the same place is a measure of the zero-sequence impedance, not between the relay and the fault, but between the relay and the grounding point or points. Line-to-ground voltage and line current are more suitable relaying quantities; but, since, for a given fault location and line current, the line-to-ground voltage depends not only upon the current in the faulted phase but also on the amounts of zero-sequence current in the protected circuit and in any parallel circuits which have zero-sequence mutual impedance with the protected circuit, the relay voltage must be compensated for the effects of these variables.[D86] Three ground distance relays are required in place of one ground overcurrent relay. Since the resistance of a ground fault may be high, reactance elements are superior to impedance elements for distance measurement, but these must be supplemented by a starting element. If a ground fault with considerable resistance is fed from both ends of the line, and if the currents from the two ends are not in phase, the balance point of the reactance element is shifted in one direction or the other from its normal position. During a two-line-to-ground fault with certain combinations of fault resistance, there is danger of the balance point moving beyond the end of the protected section; therefore, the distance ground relays must be blocked during two-line-to-ground faults.

In view of the complications mentioned above, and in view of the fact that high-speed clearing of one-line-to-ground faults is not as necessary as high-speed clearing of phase faults, distance ground relays have found very limited application.[E13]

Pilot relaying. The methods of relaying which have been described in the preceding sections of this chapter utilize currents and voltages in the vicinity of the relay location only. We now come to the consideration of methods involving currents and voltages at both ends of the protected line and hence requiring a means of transmitting information on currents and voltages from each end of the line to the other. The channels used to transmit such information are usually either wire circuits, called *pilot wires*, operating at the power-system frequency, or *carrier-current* channels using the conductors of the protected transmission line itself and operating at superposed radio frequency.

Most pilot-relaying schemes operate on one or another of the following four principles:

1. *Current comparison.* In this scheme the current entering the line at one end is compared with that leaving the line at the other end. If the currents at the two ends differ vectorially by more than a certain absolute amount or by more than a certain percentage, the difference is evidence of the existence of a fault in the protected section and causes the relay at each end to trip its breaker instantly. Under normal conditions or during external faults, the vector difference of the currents is too small to operate the relays. The current-comparison method gives no back-up protection. The pilot-wire relays must be supplemented by back-up relays—usually time-delay overcurrent relays. The comparison of currents may be made separately for each wire of the line. Or sometimes zero-sequence currents are compared, thus giving protection against ground faults only, leaving the back-up relays to clear faults not involving ground. Some of the more recent schemes compare the values of a relaying quantity which is a linear combination of the three phase currents and which is not zero during a fault of any type.
2. *Phase comparison* is similar to current comparison except that the currents entering and leaving the line are compared only as to their phase angles and not as to their magnitudes.
3. *Directional comparison.* In this scheme a directional fault-detector relay at each end of the line, actuated by any fault either on the protected line or on neighboring lines, shows the direction to the fault. If the relays at both ends of a protected line "point in," this shows that the fault is on the protected line and causes the relays at each end to trip the breakers instantly.
4. *Transferred tripping.* If an ordinary protective relay at either end of the line indicates with certainty that a fault is on the protected line—for example, by operation of the directional element and first-zone impedance element of a step-type impedance relay—then this relay trips the breaker at the near end of the line in the usual way and also sends a signal to the distant end to trip the breaker there.

The current-comparison method requires the transmission of reasonably accurate quantitative information. Usually alternating current of the power frequency is sent over pilot wires during all the time that the line is in service. The directional-comparison and transferred-tripping methods require transmission merely of qualitative information—usually only an indication which is either "on" or "off." Any type of communication channel may be used for this purpose.[F6] Direct current, audio frequency, or radio frequency may be employed. High attenuation and considerable variation of attenuation can be tolerated. The channel is needed only at the rare times of fault occurrence and may be used for other purposes in the meantime. The phase-comparison method requires a signal to be sent from each end of the line only during the positive half-cycles of fault current. The signal-transmission requirements of this method are similar to those for directional comparison and transferred tripping except that the signal, which is sent only during alternate half-cycles of fault current, always has an a-c. component and must be transmitted with negligible delay.

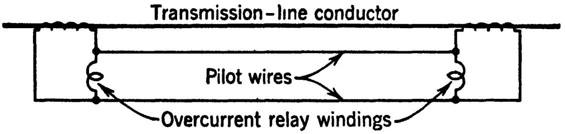
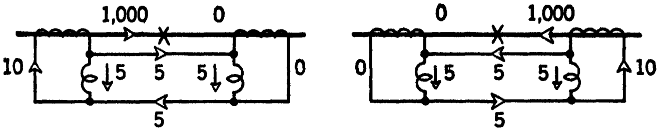


FIG. 23. Simple circulating-current pilot-wire scheme with overcurrent relays.

When pilot wires are used as the pilot channel, the current-comparison method is generally employed, because the terminal equipment is simple and reliable. When a carrier-current channel is used, phase or directional comparison is usually employed, so that variation of attenuation has no adverse effect. The transferred-tripping method is less commonly used than the other three methods.

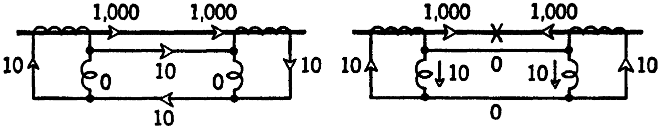
Pilot-wire current-comparison schemes are described in the next section, and carrier-current schemes, after that.

Pilot-wire current-comparison relaying. Current-comparison schemes may be divided into circulating-current schemes and opposed-voltage schemes. A simple *circulating-current scheme* is shown in Fig. 23. In analyzing the operation of this scheme, assume that the impedance of the pilot wires is negligible compared with the impedance of the relay windings and that the secondary winding of each current transformer may be regarded as a constant-current source. The current in each part of the circuit due to each current transformer may be found separately, and the currents due to both current transformers together may be found by superposition. Under the assumption of negligible pilot-wire impedance, the current due to each current transformer divides equally between the two relays, as shown in Fig. 24, parts *a* and *b*. Under both normal and external-fault conditions (Fig. 24*c*), current circulates through the pilot wires and the current transformers but not through the relays. Under internal-fault conditions (Fig. 24*a*, *b*, *d*), current flows in both relays, causing the breakers to be tripped. The relay current setting must be high enough to prevent false tripping during external faults due to inequality of the current-transformer ratios. Note that a fault on the pilot wires would cause false relay operation: a short circuit on the pilot wires would prevent tripping in the event of an internal fault, and an open circuit would cause tripping under normal load conditions.



(*a*) Internal fault fed from left-hand end only

(*b*) Internal fault fed from right-hand end only



(*c*) Through current (external fault)

(*d*) Internal fault fed equally from both ends

FIG. 24. Currents in the circuit of Fig. 23 (impedance of pilot wires neglected).

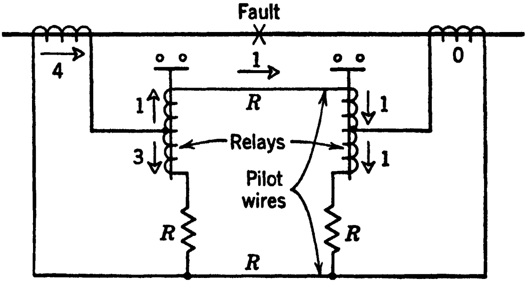


FIG. 25. Circulating-current pilot-wire scheme using current-balance relays. Each resistor has a resistance equal to that of one pilot wire. The currents are shown for an internal fault fed from the left-hand end only.

Usually the impedance of the pilot wires cannot be neglected. This impedance alters the current distribution from that shown in Fig. 24

in such a way as to cause currents in the relays during an external fault. Figure 25 shows a circulating-current scheme in which the impedance of the pilot wires is taken into account. When current is fed from one end only, it divides between the local path and the pilot-wire circuit in the ratio 3 to 1. Each overcurrent relay is actuated by the vector sum of the currents in the two windings, which is proportional to the total fault current fed from both ends. Figures 26 and 27 show the current distribution for an internal fault fed equally from both ends and for an external fault, respectively. The currents are found by superposition. In Fig. 27 the currents in the two windings of each relay are equal and opposite, and the relays are not actuated.

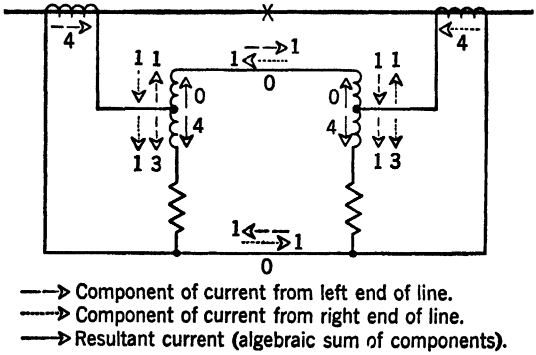

4
4
1 1
1 1
1
1
0
0
0
4
4
1 3
1 3
1
1
0
Component of current from left end of line.
Component of current from right end of line.
Resultant current (algebraic sum of components).

Fig. 26. Currents in the circuit of Fig. 25 for an internal fault fed equally from both ends.

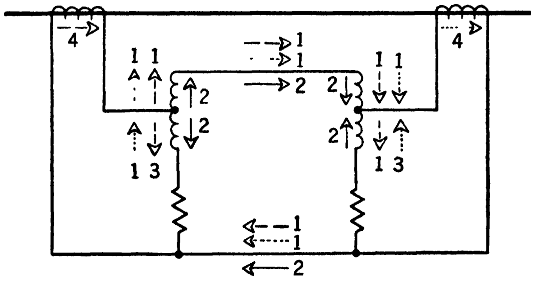


Fig. 27. Currents in the circuit of Fig. 25 for an external fault.

A simple *opposed-voltage scheme* is shown in Fig. 28. Under normal or external-fault conditions, the *IR* drops across the two resistors are equal and there is no current in the pilot wires. With an internal fault, the drops are unequal, causing a current in the pilot wires and in the relay windings, which are in series with the pilot wires. A short circuit on the pilot wires would cause false tripping under normal load condition, and an open circuit would prevent tripping during an internal fault. This is just the opposite of what would happen in a circulating-current scheme.

In any current-comparison scheme the current transformers at both ends of the protected conductor should have equal ratios at all values of current. It is not necessary that the ratios be constant at high overcurrent with resulting saturation of the cores, but the two transformers should be matched so that their ratios change by the same amount at equal overcurrents. Perfect matching cannot be counted upon. To prevent false tripping during external faults due to unequal current-transformer ratios and yet to allow sensitive setting of the relays to clear ground faults for which the fault current may be less than full-load current, the relays may be provided with restraining windings. The restraining winding carries the current of the local current transformer, while the operating winding is connected as already shown. The relay is operated when the ratio of current in the operating winding to current in the restraining winding exceeds a certain value. For a given operating-coil current, more restraint is provided by external faults than by internal faults.

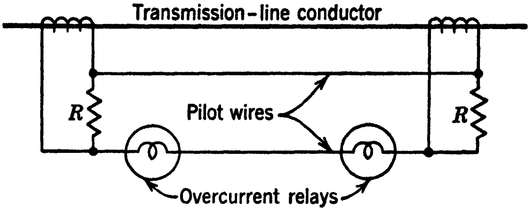


FIG. 28. Opposed-voltage pilot-wire relay scheme.

Usually insulating transformers are interposed between the pilot wires and the terminal equipment. These serve several purposes: First, they permit the secondary windings of the main current transformers to be grounded for safety. Second, they protect the terminal equipment from high voltages to ground which are sometimes induced in pilot wires—especially in overhead pilot wires used with overhead transmission lines—during faults on the line. Third, they permit the use of higher voltage and lower current on the pilot wires than in the local circuits, thus decreasing the burden on the main current transformers and permitting the ratio of the latter to be selected with regard to the needs of other relays or instruments fed by them.

The pilot-wire schemes thus far illustrated have been shown as applied to the protection of one conductor. For protection of a three-phase line against any type of fault, three such circuits are sometimes used, requiring four pilot wires—one for each phase and a fourth as common return wire. Sometimes protection against ground faults only is provided, by comparison of zero-sequence currents at the two ends of the line over two pilot wires. The use of such protection is predicated on the fact that most faults originate as ground faults. The few faults which do not involve ground must be cleared by the back-up relays. The zero-sequence currents are obtained as shown in Fig. 29. The scheme shown in this figure, with double-winding relays as described above, is extensively used by a large metropolitan system[F13] for protection of three-conductor underground cable. The pilot wires used by this company are no. 12 A.W.G. lead-covered cable with insulation rated at 500 volts. The pilot cable is run underground in center ducts, which do not have good heat-radiating capacity for power cables. This pilot-wire scheme has given very reliable protection.

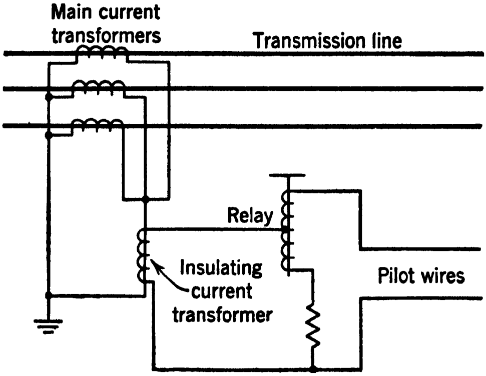


FIG. 29. The pilot-wire relay scheme of Fig. 25 applied to protection of a three-phase line against ground faults.

Several schemes have been developed recently which make it possible to protect a three-phase line against any type of fault by the use of only two pilot wires. These schemes make use of a relaying quantity (current or voltage) which is some linear combination of the three line currents and which is much greater during any type of fault than it is under normal conditions. The relaying quantities at the two ends of the line are compared with one another. In the Westinghouse Type HCB pilot-wire relay,[F9] the relaying quantity is $k_1\mathbf{I}_1 + k_0\mathbf{I}_0$, where $\mathbf{I}_1$ is the positive-sequence current, $\mathbf{I}_0$ is the zero-sequence current, and k_0 is a constant greater than k_1. The relaying current is obtained from suitable sequence filters. In the General Electric Type CPD relay,[F10] the relaying quantity is $N_p(\mathbf{I}_b + 2\mathbf{I}_c) - 3N_0\mathbf{I}_0$, where N_0 is greater than N_p. This current is obtained from a tapped autotransformer as shown in Fig. 30. In both these schemes, the magnitude of the relaying quantity varies with the phase or phases involved in the fault.

The arrangement of a pilot-wire scheme using Type HCB relays is shown in Fig. 31. A means of supervising the pilot wires is provided by a d-c. source and two lamps. A short circuit on the pilot wires extinguishes one lamp; an open circuit, both lamps.

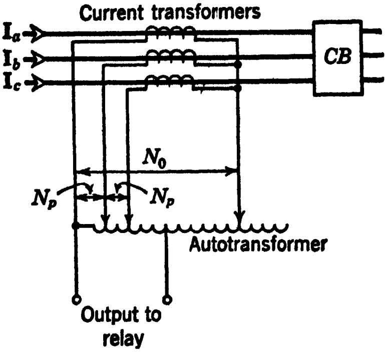


FIG. 30. Relaying quantity $N_p(\mathbf{I}_b + 2\mathbf{I}_c) - 3N_0\mathbf{I}_0$ is obtained by a tapped autotransformer in the General Electric Type CPD high-speed a-c. pilot-wire relay. Taps N_p adjust the sensitivity to phase faults; tap N_0, to ground faults.

Pilot-wire relaying provides simultaneous high-speed tripping of the breakers at both ends of the line for faults anywhere on the line. It is

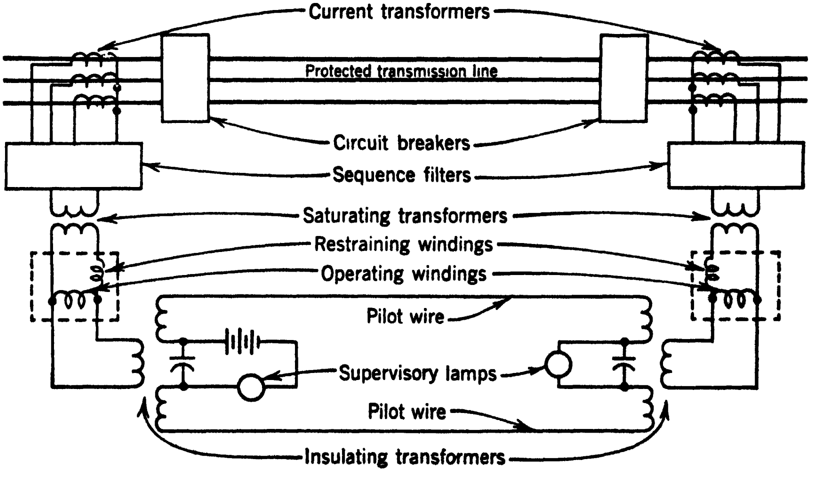


FIG. 31. Alternating-current pilot-wire scheme using Westinghouse Type HCB relays—schematic circuit.

particularly suitable for the protection of short lines. Short lines cannot be protected properly by high-speed impedance relays, because the difference in indicated impedance between faults in the different zones is too small a fraction of the indicated impedance under normal conditions. For short lines, pilot-wire relaying is less expensive than carrier-pilot relaying because the terminal equipment is simpler and cheaper. Furthermore, because of its simplicity, it is more reliable. As the length of the protected line increases, however, the cost of pilot wires increases and their reliability decreases, so that for lines longer than perhaps 10 to 25 miles it is cheaper and more satisfactory to use carrier-current pilot relaying.

Carrier-pilot relaying. On long lines carrier-pilot relaying is cheaper and more reliable than pilot-wire relaying, even though the terminal equipment is more expensive and more complicated than that required for use with pilot wires. In some installations the expense of carrier equipment chargeable to relaying may be reduced by joint use of the carrier channel for regular or emergency telephone communication, for supervisory control, and for telemetering, as well as for relaying.[G6, 14, 16, 27] Furthermore, in some installations, the coupling capacitors required for the carrier channel may be used also as capacitance potential devices, taking the place of the expensive potential transformers which would otherwise be required for furnishing voltage to the protective relays.

Contrary to the common practice in pilot-wire relaying, a *quantitative* comparison of the currents at the two ends of the line is not made in carrier relaying. Instead, *the simplest possible signal is transmitted; that is, the carrier is either on or off.* Hence operation is not adversely affected by considerable variation in the strength of the received carrier signal.

Figure 32 shows schematically the equipment required for a carrier-current relay system. At each end of the protected transmission line there are protective relays, a transmitter-receiver unit, a coupling capacitor, and a line trap.

The *relays* are of high-speed type, and there may be separate relays for each phase and for ground. The relay circuits will be described in detail subsequently.

The *transmitter-receiver unit* resembles a simple radio-telegraph transmitter and receiver. The transmitter consists of a master oscillator and a power amplifier. Its output is from 5 to 40 watts at a frequency which may be adjusted to any value between 50 and 150 kc.p.s. The oscillator is turned off either by connecting its screen

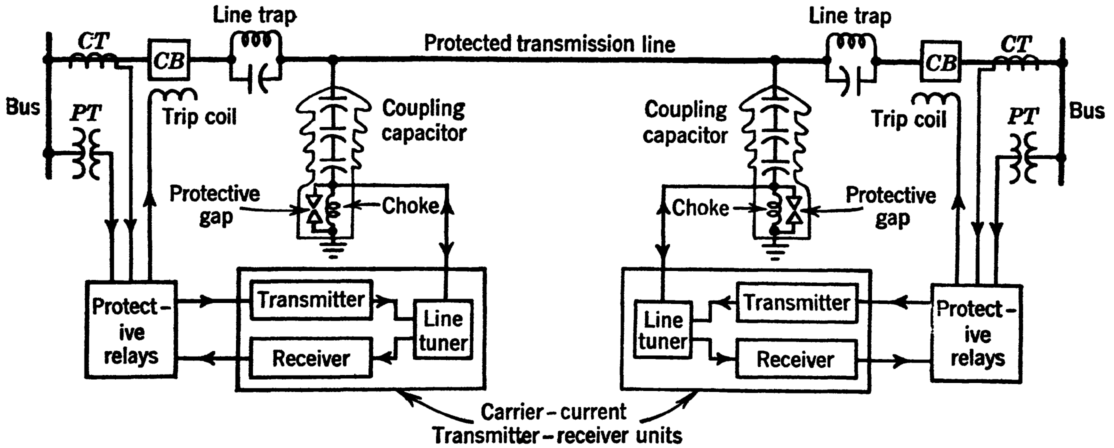


FIG. 32. Typical carrier-current pilot relay system—block diagram. (Adapted from Ref. A14 by permission of the Westinghouse Electric Corporation)

grid to a negative potential or by removing the plate-to-cathode potential. The receiver has a detector and sometimes a relay tube also. The output of the receiver goes to the protective relays. Each receiver on a two-terminal line is tuned to the same frequency as the transmitter at the other terminal. Either the same frequency may be used for transmission in both directions, or a different frequency may be used in each direction if this is desired for the nonrelaying functions of the carrier channel. On a multiterminal line, however, all transmitters and receivers should be tuned to the same frequency so that each receiver will respond to the transmitter at any other terminal and, incidentally, to the transmitter at the same terminal. A tuner is provided for matching the transmitter and the receiver to the transmission line. The transmitter-receiver unit is sometimes installed outdoors near the coupling capacitor and connected to the latter through a short overhead wire; it is sometimes installed indoors and connected to the coupling capacitor through a coaxial cable. The station storage battery is used as the power supply.

The transmitter-receiver unit is connected to the high-voltage transmission-line conductor through a *coupling capacitor*, which consists of a porcelain-clad, oil-filled stack of capacitors connected in series to withstand the high line voltage and grounded through an inductance coil (about 100 mh.). The capacitor stack has a capacitance of about 0.001 μf., giving an impedance of a few million ohms to the 60-cycle power current but only a few thousand ohms to the carrier frequency. The inductance coil, on the other hand, offers a low impedance to 60-cycle current and a high impedance to carrier frequency. Thus the carrier transmitter-receiver unit is effectively insulated from the transmission line and grounded at 60 cycles, yet connected to the line and insulated from ground at carrier frequency. The reactance of the coupling capacitor to the carrier current is compensated by adjustable series inductance in the line tuner.

A *line trap*, consisting of a parallel combination of inductance and capacitance tuned to the carrier frequency, is connected in series with the line conductor at each end of the protected transmission line. The purpose of the trap is to confine the carrier power to the protected section, thus assuring ample signal strength unaffected by switching operations or line-to-ground faults on other circuits.

The *carrier circuit* may consist either of two of the three line wires or of one wire with ground return. The ground-return circuit has greater attenuation and greater interference than the metallic circuit; but, on the other hand, it requires only half as many coupling capacitors and wave traps. It is usually satisfactory for relaying purposes, but the metallic circuit is preferable for communication.

The presence of branch lines or tapped loads sometimes causes troublesome reflection. Rather than go to the expense of isolating such branches with line traps, one can usually find a carrier frequency which gives satisfactory transmission. The greatest transmission loss which can be tolerated is about 35 db. Carrier transmission on power cables generally is unsatisfactory because of high attenuation.

Carrier relay circuits for directional comparison. Carrier-pilot relay schemes of the directional-comparison type operate according to the following general principles. Upon the occurrence of a fault, either in the protected section of line or in a nearby section, non-directional fault-detector relays are actuated at each line terminal through which power is fed to the fault. Each fault-detector relay turns on the carrier-current transmitter at its own terminal. If, however, the directional relay at any terminal shows that fault power is flowing into the protected line section, that relay turns off the carrier-current transmitter. The presence of carrier on the line serves to block tripping at all terminals. During an external fault, power will flow out of the line at one terminal, and a carrier signal transmitted from that terminal will prevent tripping at the other terminals, where power is flowing in. During an internal fault, on the other hand, power will usually flow into the line from all terminals, with the result that all carrier transmitters will be turned off and the relays at all terminals will be free to trip instantaneously. If, at the time of an internal fault, a breaker is already open at one terminal, or if there is no power source there, then the fault detector will not turn on the carrier transmitter there; thus tripping will not be prevented by the fact that no power flows into the line at that terminal to make the directional relay turn off the carrier transmitter there.

Note that *carrier is transmitted only upon the occurrence of a fault and is used only to prevent tripping in the event of an external fault.* Therefore, the possible short-circuiting of the carrier channel by an internal fault cannot hinder the operation of the relays to clear that fault.

Carrier-pilot relaying closes the trip circuits of the breakers at both terminals of a line within from 1 to 3 cycles after the occurrence of an internal fault, whether it be a phase fault or a ground fault.

The directional-comparison carrier-pilot relay schemes in current use are built around standard three-zone step-type distance relays, such as the Westinghouse Type HZ or HZM or General Electric Type GCX or GCY, for phase-fault protection. These relays act in the usual manner to clear first-zone faults instantaneously and, for back-up protection, to clear third-zone faults with time delay; but time delay is avoided for end-zone phase faults through bypassing the second-zone timer contacts by carrier-controlled contacts. Separate carrier and back-up relays are used for ground faults. The time-delay ground relays and high-speed distance phase relays may be installed initially without carrier, and later, when protective requirements become more stringent, carrier equipment and auxiliary relays may be added to extend the high-speed protection to end-zone phase faults and to ground faults. Moreover, if, after carrier equipment has been installed, it becomes necessary to take it out of service temporarily for maintenance, the high-speed distance relays can be left in service, thus affording the second-best kind of relay protection.

Supplementary relays may be added to prevent tripping under out-of-step conditions, as described in Chapter X.

Two of the directional-comparison carrier-pilot relay schemes will now be described in more detail.

Westinghouse Type HZ carrier-pilot relays comprise three Type HZ impedance relays, each having three impedance elements, a directional element, a timer, and auxiliary relays; a high-speed directional overcurrent ground relay, having two overcurrent elements and a directional element; a ground back-up relay; and a carrier auxiliary relay, consisting of a receiver relay and d-c. auxiliary relays.

The Type HZ impedance relays operate in the usual way to clear phase faults, except that the second-zone timer contacts are bypassed during internal faults, so that all internal faults are cleared without delay. During external faults, the presence of carrier current on the line prevents bypassing of the timer contacts. However, the second- and third-zone impedance elements can still trip with time delay to provide back-up protection. Carrier transmission is started by any of the third-zone impedance elements and is stopped by the closing of the contacts of both the directional element and the second-zone impedance element of any HZ relay.

In the event of a ground fault, carrier transmission is started by an instantaneous zero-sequence overcurrent relay and is stopped by an instantaneous zero-sequence directional overcurrent relay. A separate ground relay is used for back-up protection.

The *contact circuits* of the relays are shown in Fig. 33. In addition to the phase and ground relays, there are the receiver relay and two auxiliary relays (*CSG* and *CSP*). The receiver relay has an operating coil, *RRT*; a holding or restraining coil, *RRH*, operated by the output of the carrier receiver; and two front contacts, *RRG* and *RRP*. The holding coil, when energized, prevents the operating coil from closing the contacts.

The *trip circuits* are shown in the upper part of the figure. For phase faults, there are three tripping paths per phase which are independent of carrier: for first-zone faults, through D and Z_1 with no delay; for second-zone faults, through D, Z_2, and T_2 with delay; for third-zone faults, through D and T_3 with greater delay. When carrier is used, there is an additional tripping path through D, Z_2, and *RRP*, the latter being contacts on the receiver relay which bypass the timer contacts T_2, thereby permitting instantaneous tripping. For ground faults there is a tripping path, independent of carrier, through contacts D_{01} and I_{01} of the time-delay directional overcurrent back-up relay. There is also a carrier-controlled path through contacts D_0 and I_{02} of an instantaneous directional overcurrent relay and contacts *RRG* of the receiver relay. The receiver relay is actuated by an auxiliary relay *CSG* or *CSP*, as will be shown presently.

The *carrier-current control circuits* are shown in the lower part of the figure. These circuits have to do with starting and stopping the carrier transmitter and with the actuating and restraining of the receiver relay to allow or to prevent instantaneous tripping. Upon the occurrence of a phase fault, contacts Z_3 of the third-zone impedance element start carrier transmission by applying positive potential to the plate of the oscillator tube. If the fault is in the tripping direction but not beyond the balance point of the second-zone impedance element, relay *CSP* is energized. This relay opens its back contacts, stopping transmission of carrier signal by raising the cathode potential and energizing the receiver-relay operating coil *RRT* by removing the short circuit from it. Unless restrained by the receiver-relay holding coil *RRH*, the receiver relay closes its contacts, *RRP* and *RRG*, to permit instantaneous tripping. Upon the occurrence of a ground fault, contacts I_{03} of the instantaneous ground relay start transmission of carrier. If the ground fault is in the tripping direction, relay *CSG* is energized, and its back contacts stop carrier transmission and energize coil *RRT*, just as relay *CSP* does in case of a phase fault. Unless restrained by received carrier signal, the receiver relay closes contacts *RRG* to permit instantaneous tripping.

The circuits can be arranged to give *ground preference* by connecting the front contacts of relay *CSO* in parallel with the back contacts of *CSG* as shown in broken lines. Then carrier transmission can be

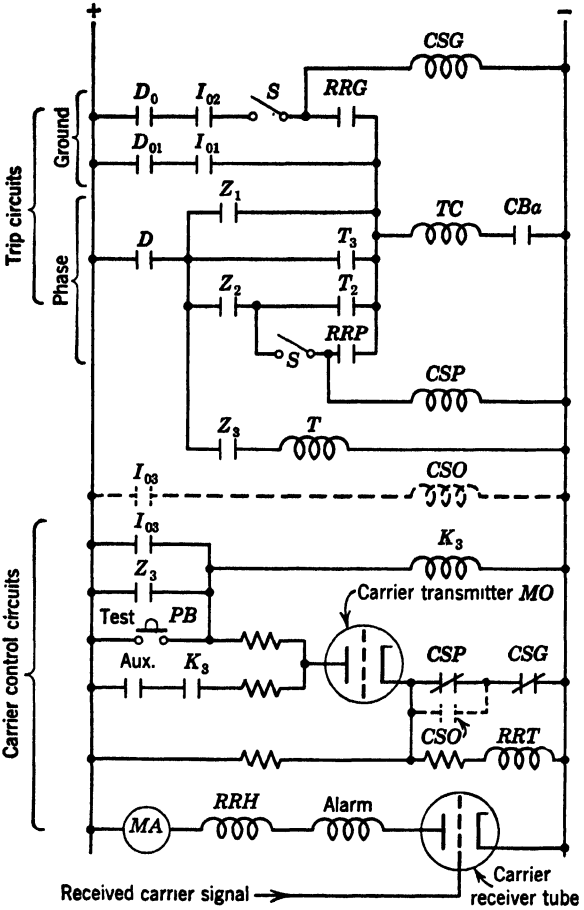


FIG. 33. Simplified schematic diagram of contact circuits of Westinghouse carrier-pilot relay scheme, using Type HZ impedance phase relays and overcurrent ground relays. The a-c. voltage and current circuits are omitted. Only one phase relay is shown.

Aux.	Contacts for controlling the carrier transmitter for auxiliary uses of the carrier channel—for example, for telemetering.
CBa	Auxiliary switch of circuit breaker, used to open trip circuit when breaker opens.
CSG	Contactor switch (auxiliary relay) used in connection with ground relay.
CSP	Contactor switch used in connection with phase relay.
D	Directional element of phase relay.
D_0	Directional element of ground relay.
D_{01}	Directional element of ground back-up relay.
I_{01}	Overcurrent element of ground back-up relay.

started and stopped by the ground relays, regardless of the action of the phase relays. This is sometimes necessary to prevent false tripping during an external ground fault through operation of the phase relays, especially if the latter have single-phase directional elements supplied with star current.[G20]

For making *carrier tests* a pushbutton *PB* is provided, by means of which the carrier transmitter may be turned on. If the equipment is in good working order, a carrier signal will be received at each end of the line, causing an alarm relay and a milliammeter to be energized. The alarm relay has a minimum operating current greater than the minimum current required to operate the receiver relay, so that an indication of impending trouble can be obtained before actual failure occurs.

The carrier equipment may be removed from service by a two-pole switch *S* which opens the carrier-controlled trip paths. The type HZ relays then give phase-fault protection which is instantaneous except for end-zone faults, and the ground back-up relay gives time-delay ground-fault protection.

When the carrier channel is being used for other services than relaying, the carrier transmitter is started by contacts marked "Aux."; but, when the channel is needed for protective relaying, relay K_3 takes control of the transmitter away from the other services.

I_{02}	Instantaneous overcurrent element of ground relay.
I_{03}	Second instantaneous overcurrent element of ground relay, used to start carrier transmission.
K_3	Relay to prevent the use of carrier channel for other purposes when it is required for relaying.
MA	Milliammeter for checking carrier channel.
MO	Master oscillator.
PB	Pushbutton.
RRG	Contacts of receiver relay used in connection with ground relay.
RRH	Receiver relay holding coil. When this coil is energized with received carrier signal, it prevents *RRT* from closing the contacts.
RRP	Contacts of receiver relay used in connection with phase relays.
RRT	Receiver relay operating coil.
S	Switch which is opened to put the carrier equipment out of service.
T	Timer coil of phase relay. (Actually the timer coil is energized with a-c. fault current and not with direct current as shown here for the sake of simplicity.)
T_2, T_3	Timer contacts.
TC	Trip coil of circuit breaker.
Z_1	First-zone impedance element of phase relay.
Z_2	Second-zone impedance element of phase relay.
Z_3	Third-zone impedance element of phase relay.
+, −	D-c. bus from station battery, polarity as marked.

Mho carrier relaying.[D32, 33, G24] Another directional-comparison carrier-pilot relaying equipment uses the General Electric Type GCX reactance relays or Type GCY mho relays for phase-fault protection. When the mho relays are employed with carrier, an offset mho element OM_3 starts carrier transmission. This element is connected reversed so as to give the characteristic shown in Fig. 34 (instead of that in Fig. 21) because carrier blocking is required only for external faults.

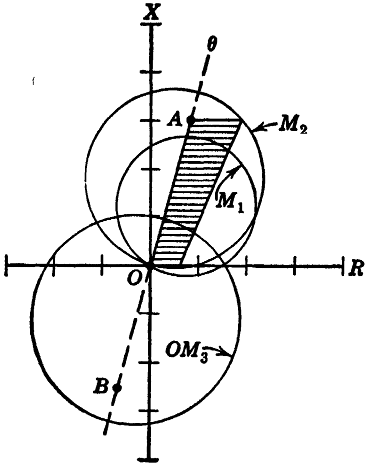


Fig. 34. Characteristics of mho distance relay with reversed connection of third-zone element OM_3.

The circuits for mho carrier relaying are shown schematically in Fig. 35. Responding to phase faults, there are three mho relays (only one of which is shown), each having a first-zone mho element M_1, a second-zone mho element M_2, a third-zone reversed offset mho element OM_3, and a timer T. Responding to ground faults, there are two directional ground relays GD_1 and GD_2 and a nondirectional ground relay G_2 used for carrier relaying, and also a ground back-up time-delay relay GB.

Noncarrier relaying of ground faults is effected by relay GB. Noncarrier tripping of phase faults is accomplished through either of three paths: first zone, instantaneously through mho-element contacts M_1; second zone, with time delay, through mho-element contacts M_2 and timer contacts T_2; third zone, with greater time delay, through mho-element contacts OM_3 and timer contacts T_3. The timer T is started by either the second-zone mho element M_2 or third-zone mho element OM_3 because, with the characteristic of OM_3 reversed, its tripping area does not enclose all the tripping area of M_2.

The trip circuits are opened by relay OB for out-of-step blocking, as described in Chapter X.

Carrier-controlled tripping is initiated for phase faults by mho element M_2 and for ground faults by directional ground relay GD_2, which closes its contacts for faults in the forward direction (that is, on or beyond the protected line). The tripping path is not completed, however, unless the contacts of receiver relay R are closed. These contacts are held open when either or both of two windings R_1 and R_2

are energized. In the absence of a fault, they are held open by current in winding R_1 If a fault in the tripping direction occurs, this current is broken by contacts M_2 or GD_2, and contacts R close to permit tripping unless a carrier signal, received from another terminal in event of an external fault, energizes winding R_2, thus holding contacts R open and preventing tripping. The use of winding R_1 prevents a "race" between the opening of contacts R by received carrier and the closing of contacts M_2 or of GD_2 and G_2 by local relays. If the carrier equipment is out of service, switch SC should be opened to prevent tripping.

Normally the screen grid of master oscillator tube MO in the carrier-current transmitter is connected to the negative side of the control battery, and carrier is not transmitted. In the event of an external fault in the reverse direction, the transmitter is turned on by opening of the back contacts of either GD_1 (for ground faults) or OM_3 (for phase faults), thereby connecting the screen grid to the positive side of the battery. Relays GD_1 and OM_3 operate mainly for faults in the reverse direction, although OM_3 operates also for nearby faults in the forward direction (internal faults). If the fault is in the forward direction, relay GD_2 or M_2 stops or prevents carrier transmission by short-circuiting contacts OM_3 and GD_1, thereby reapplying negative potential to the screen grid. Carrier transmission prevents tripping of circuit breakers at the other terminal or terminals of the line.

Carrier-relay circuits for phase comparison. Phase-comparison carrier relays, like some pilot-wire relays, utilize a single-phase relaying quantity, which is obtained by linear combination of the line currents through a circuit called a *filter*. The phase difference between the relaying quantities at the opposite ends of the protected transmission line determines whether the circuit breakers should be tripped. During normal conditions or during external faults, the currents entering the line at one end are substantially equal to those leaving the line at the other end; or, in other words, the currents entering the line at one end differ in phase by approximately 180° from those entering the line at the other end: therefore, the relaying quantities at the two ends are about 180° apart. During an internal fault, however, the relaying quantities at the two ends of the line have some other phase difference (usually near zero). The existence, at either end of the line, of a relaying quantity large enough to indicate the presence of a fault will trip the circuit breaker unless there is received from the other end a blocking signal caused by a relaying quantity differing in phase by approximately 180° from that at the near end.

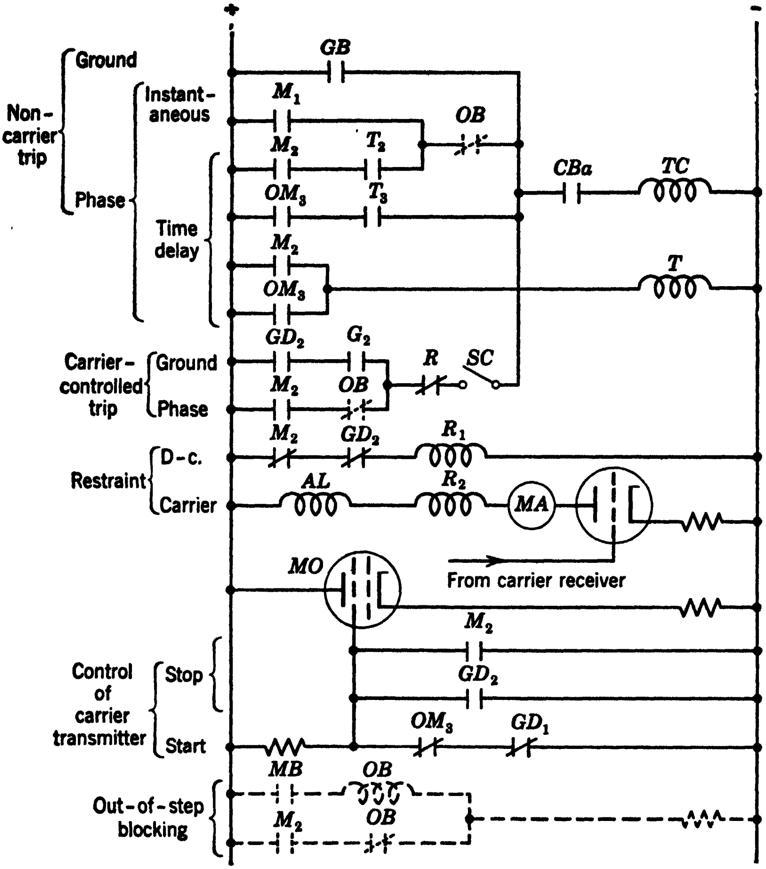


FIG. 35. Simplified schematic diagram of direct-current circuits of directional-comparison carrier-pilot relay scheme using G.E. Type GCY distance relays. Only one of the three phase relays is shown, and several auxiliary relays are omitted.

AL	Alarm relay.
CBa	Auxiliary switch on circuit breaker, closed when circuit breaker is closed.
G_2	Nondirectional overcurrent relay.
GB	Ground back-up relay.
GD_1	Directional ground relay which operates for reverse (external) faults.
GD_2	Directional ground relay which operates for forward (internal) faults.
M_1	First-zone mho unit.
M_2	Second-zone mho unit.
MA	Milliammeter for carrier test.
MB	Offset mho unit for out-of-step blocking.
MO	Master oscillator tube of carrier transmitter.
OB	Out-of-step blocking relay.

The existence of a fault of any type on the protected line or on a neighboring circuit produces a large enough output from the filter to actuate a fault-detector relay. This relay turns on the carrier-current transmitter, which, however, transmits only during alternate half-cycles. If the fault is external, the transmitter at the other end transmits during the half-cycles when the local transmitter is inactive, and a blocking signal is received all the time, alternately from the near end and from the far end. If the fault is internal, the carrier signal received from the far end more nearly coincides with the local signal, and there are substantial portions of each cycle during which no blocking signal is present. Under this condition, the local circuit breaker is tripped. The same action occurs at each end of the line unless the fault is fed only from one end. With feed from one end only, no carrier is transmitted from the other end, and the breaker there is not tripped; while, at the feeding end, no blocking signal is received, and the breaker is tripped.

In order to show in more detail how these functions are performed, the *Westinghouse Type HKB relay*[G25] will be taken as an example.

A sequence filter similar to that on the Type HCB pilot-wire relay and having a single-phase output $k_1\mathrm{I}_1 + k_0\mathrm{I}_0$ is used. The output of this filter is connected to the winding of a fault-detector relay (*FD* in Fig. 36) and to the grids of two thyratrons, V_1 and V_2. If the output of the filter is great enough, the fault-detector relay applies d-c. voltage through contacts *FD*-1 to the plates of the thyratrons, while another pair of contacts (not shown) interrupts any other function (such as telephony or telemetering) for which the carrier-current channel may be used when not required for relaying. When the grid of V_1 becomes positive, as a result of filter output voltage, V_1 fires, and its plate current rapidly reaches a value determined by the d-c. supply voltage and by resistors R_p and R_c. On the next half-cycle, the grid of V_2 becomes positive, and V_2 fires. When this occurs, the coupling between the plates of the two thyratrons through capacitor C makes the plate potential of V_1 momentarily negative, causing V_1 to stop conducting. The two thyratrons continue to conduct alternately. The wave form of plate current of each thyratron

---

OM_3	Third-zone offset mho unit.
R	Receiver-relay contacts.
R_1, R_2	Receiver-relay windings.
SC	Carrier-trip cutoff switch.
T	Timer winding.
T_1, T_2	Timer contacts.
TC	Trip coil of circuit breaker.

is a square wave of constant amplitude and of power frequency. The voltage across R_c, the cathode resistor of V_1, is applied to the plate of the oscillator tube in the carrier transmitter and causes the transmission of carrier on alternate half-cycles of the power-frequency filter output. The voltage appearing across the cathode resistor R_c' of the other thyratron V_2 in the intervening half-cycles is connected in the grid circuit of a vacuum tube known as the relay tube. In series with this voltage is the voltage E_R due to the d-c. output of the carrier receiver. These two voltages are in opposition: the voltage derived from the local relaying quantity tends to make the relay tube conduct, whereas that from the carrier receiver, being of opposite polarity and greater magnitude, prevents the tube from conducting if both voltages are applied simultaneously, as they are during an external fault. During an internal fault, however, the two voltages are applied at different times, and the tube conducts during the portions of the cycle when the local signal occurs in the absence of the distant signal. The pulsating plate current of the relay tube then induces a voltage in the secondary winding of transformer *TR* and operates tripping relay *R*, which trips the circuit breaker.

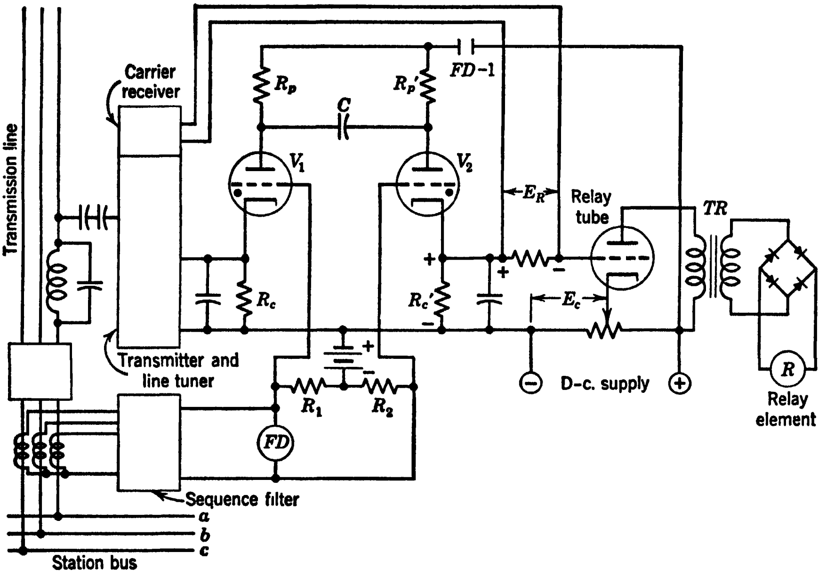


FIG. 36. Basic circuit of Type HKB phase-comparison carrier-pilot relay. (From Ref. G25 by permission)

Figure 37 shows the wave forms in several parts of the circuit and indicates how the phase relationships during an internal fault differ from those during an external fault. It is assumed here that the phase difference for an internal fault is zero.

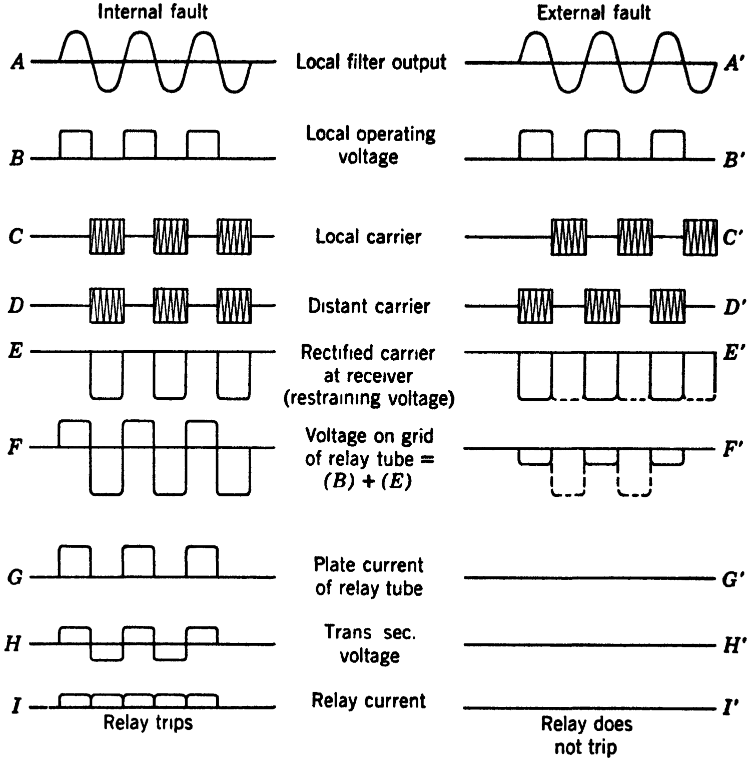


Fig. 37. Wave forms in circuits of Type HKB phase-comparison carrier-pilot relay during internal and external faults. Broken lines are only for operation with the same carrier frequency in both directions. (From Ref. G25 by permission)

The same carrier frequency may be used for transmission of signals in both directions, or two different frequencies may be used, since reception from the local transmitter is not required.

Figure 38 shows how the current in the tripping relay varies as a function of the phase difference between the relaying quantities at the two ends of the protected line. Tripping occurs if the relay current exceeds the pick-up value, which it does for all values of phase angle except in the zone 180° ± 30°. The blocking zone is much narrower than the tripping zone and can be so without any risk of false operation, for, unless there is an internal fault, the two relaying quantities must be very nearly 180° apart.

The operating time of this equipment is 1 to 3 cycles and averages 2.5 cycles.

Other phase-comparison relays[G22, 29, 31, 33] have been built differing in detail but accomplishing much the same result.

The phase-comparison system of carrier-pilot relaying has several advantages over the directional-comparison systems. It operates on line currents only and does not require voltage from potential transformers. It is simpler and cheaper, having few relays and tubes; only two pairs of contacts at each terminal are used for tripping. It will not trip during swings or out-of-step conditions or because of zero-sequence current induced from a parallel line if there is no fault on the protected line. The directional-comparison system has the advantages of being applicable to multiterminal lines, of providing better discrimination between faults on the protected line and tapped loads or faults on tapped circuits, and of being able to trip on smaller ground-fault currents.[A21]

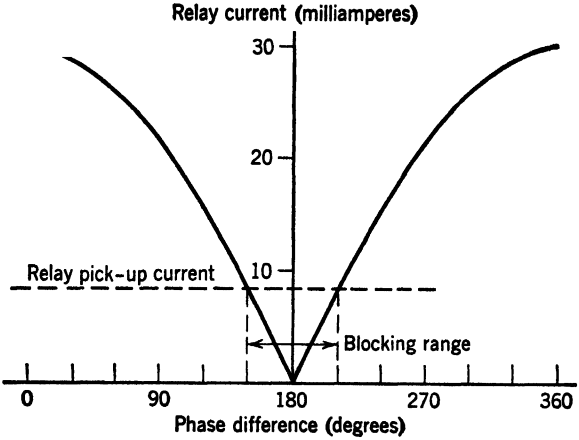


FIG. 38. Current in tripping relay of phase-comparison carrier-pilot relay system as a function of the phase difference between the relaying quantities at opposite ends of the protected line. (From Ref. G25 by permission)

Protection of tapped lines.[B20, 23] It is more difficult to give high-speed relay protection to tapped lines (lines having three or more terminals) than to untapped, or two-terminal, lines. *Timed overcurrent relays* can be used, but the time delays required for selectivity may be greater than permissible.

The use of *high-speed impedance relays* on tapped lines presents some difficulties not encountered on two-terminal lines. Even though there is a power source at only one terminal, the impedances from this terminal to the other two terminals may be unequal. The first-zone impedance element can be set to trip for faults at distances up to 90% of the distance to the less remote terminal. The end zone at the more remote terminal may then be unduly long. The second-zone impedance element must be set to trip for faults beyond the more remote terminal. With this setting it may reach so far beyond the less remote terminal as to include another whole line section, whereas for proper selectivity it should cut off somewhere in the first zone of that next line section. A similar problem exists with the third-zone element. A second difficulty is that the balance point beyond the tap is shifted according to the amount of current in the tap. If there is a power source at the tap, current fed to the fault from this source moves the balance point closer to the relay. On the other hand, load current drawn from the tap during a fault shifts the balance point away from the relay and may cause the relay to overreach.

Pilot relaying based on directional comparison is usually satisfactory on tapped lines and will prevent the relays from overreaching. Usually, when an internal fault occurs, power flows into the line at all terminals where there are sources, and then tripping is permitted. If, however, there is a parallel tie between two of the terminals, it is possible that during an internal fault near one of these terminals power may flow out the other terminal and over the parallel tie to the fault. If this should happen, tripping would be blocked at all terminals. However, if the relays used in the directional-comparison scheme are step-type distance relays of which only the second-zone elements are pilot-controlled, the fault would be cleared sequentially, as follows: The breaker at the terminal nearest the fault would be tripped by the first-zone impedance element, which is not pilot-controlled. As soon as this breaker opened, power would cease to flow out the terminal where it did, blocking would be removed, and the relays at the terminals where the breakers were still closed would immediately initiate tripping.

Pilot relaying based on current comparison is ideal in principle because the breakers at all terminals are tripped when the net flow of fault power is into the line, even though power may be flowing out at one terminal. Such relaying is satisfactory in practice provided that the pilot wires are not too long. In the circulating-current scheme the pilot wires from all terminals should be connected in parallel; in the opposed-voltage scheme a series pilot circuit should be used.

Summary of good practice in transmission-line relay protection. On important high-voltage lines, high-speed fault clearing is generally necessary, or at least advisable, for reasons of system stability and for other reasons. On many such lines high-speed distance relays are used, which give high-speed clearing at both ends of the line for faults in the middle eight-tenths of the line length, and sequential clearing of faults in the two end zones each one-tenth of the line in length. The ground relays are usually of either the slow-speed or the high-speed overcurrent types. Fortunately, from the standpoint of stability, high-speed clearing is not so necessary for one-line-to-ground faults as for phase faults. If the stability situation is so critical that high-speed clearing of ground faults and of end-zone phase faults is required, then carrier-pilot relaying is generally employed. On long or heavily loaded lines, the distance relays (whether used with or without carrier) should be of a kind not too susceptible to trip on swings from which the system will recover.

On short but important lines, pilot-wire relaying is appropriate. Its use has grown greatly since relays were developed that give protection against all types of internal fault by means of a pilot channel consisting of only two small wires (for example, a telephone circuit).

On unimportant lines, slow-speed overcurrent relays are ordinarily used.

Apparatus protection. Some of the protected sections of a power system (Fig. 1) consist of such apparatus as generators and transformers. Although the protection of transmission lines is one of the most important, difficult, and interesting branches of the relay art, the protection of apparatus is also important. Faults occur less frequently in apparatus than on lines, but the damage done to apparatus when faults do occur therein usually takes much more time and money to repair than are required to repair the damage done by faults on lines. Indeed, many faults on overhead lines, if cleared rapidly, cause practically no damage, and, on that account, rapid reclosing of breakers is feasible. A fault in a generator or transformer, on the other hand, always damages the apparatus to such an extent that it must be removed from service for inspection and repair. However, the extent of the damage can be minimized by rapid fault clearing. For example, a ground fault in a generator, if cleared quickly, would necessitate only the replacement of a few armature coils—a relatively simple repair operation. Slow clearing, on the other hand, would result in burning of the iron laminations, requiring the iron to be restacked—a much longer and costlier task. As another example, internal faults in oil-insulated transformers should be cleared fast enough so that an oil fire does not ensue.

Fast clearing of faults on apparatus is important not only to minimize the damage to the apparatus but also to lessen the disruption to power service from reduced voltage and from instability.

Generator protection. A variety of abnormal operating conditions may arise in generators, among which are short circuits or open circuits in the windings or in the leads from the generator to the bus, overcurrent, overheating, motoring, loss of field, overspeed, underspeed, bearing overheating, single-phase or unbalanced-current operation, overvoltage, undervoltage, and loss of synchronism. Protective relays are available for detecting each of these conditions and either giving an alarm or shutting down the machine. In unattended stations protection is provided against most of these conditions by shutting down the machine. In attended stations less complete protection is needed. Only protection for clearing short circuits in the armature (stator) windings and leads is considered here. Protection against loss of field and loss of synchronism is considered in Chapter X.

When a short circuit occurs on the armature winding or leads of a generator, the circuit breaker connecting the generator to the bus should be opened immediately to prevent disruption of service on the rest of the power system and to open the feed to the fault from other generators on the system. At the same time, the field circuit should be opened to prevent the generator from feeding its own fault. If the generator has a grounded neutral, it is advisable to provide a neutral circuit breaker and to trip this breaker simultaneously with the armature and field breakers, for the purpose of immediately stopping the current in a ground fault, which may persist after the field breaker is open on account of the slow decay of flux and also because of residual magnetism. In addition to tripping the three breakers mentioned, the protective relay may, if desired, release fire extinguishers and shut down the prime mover.

The best method of detecting short circuits in the armature windings or leads of a generator is to use differential relays to compare the currents at opposite ends of each phase winding (see Fig. 39). Normally the currents at the two ends are equal, but during an internal fault they are unequal. The difference of the two currents passes through the operating winding of the relay.

The difference current (representing the fault current) appears in the event of either a phase fault or a ground fault (if the generator neutral is grounded). However, a ground fault near the neutral end of the winding will result in only a small fault current because of the small e.m.f. of the short-circuited portion of the winding. This current is also reduced by the use of neutral grounding impedance.

The sensitivity of the relay (the pick-up current for which it may be set) is limited by the necessity of preventing false operation on external faults because of differences in the current-transformer characteristics.

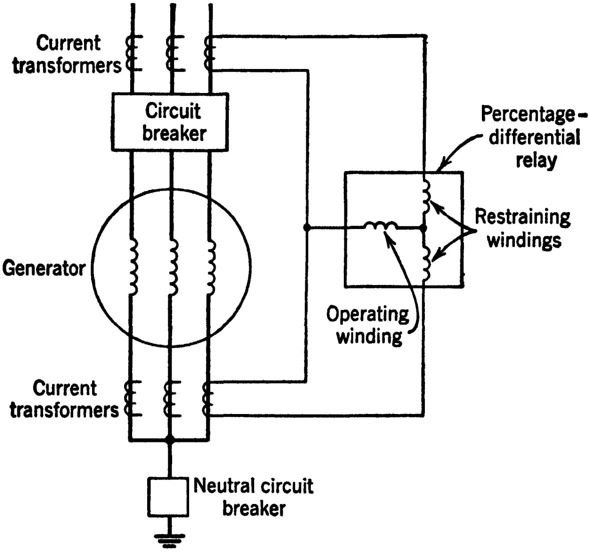


FIG. 39. Generator protection by percentage-differential relays. (Connections of relays are shown for only one phase.)

To decrease the likelihood of the relay operating on external faults, without preventing it from responding to low-current internal faults, restraining windings are added. The result is a *percentage-differential relay* (also known as a *ratio-differential relay*), which operates when the current in the operating winding exceeds a certain percentage of the current in the restraining windings—on generator relays usually 10% of the smaller restraining current.

On generators having two windings in parallel per phase, an additional percentage-differential relay may be used on each phase to compare the currents in the two parallel paths. This relay will detect short circuits between parts of the same phase winding and also open circuits (neither of which are detected by the main differential relays).

A typical percentage-differential relay is the Westinghouse Type CA.

Overcurrent relays are used to clear faults on some small machines which do not have both ends of the windings brought out and as back-up to differential relays. Overcurrent protection is a very poor substitute for differential protection as a means of clearing internal faults.

Differential protection is applied not only to generators but also to large motors and synchronous condensers. It is not applicable to synchronous converters because of their different type of armature winding.

Transformer protection. Transformers require protection against internal faults and against overheating caused by overloading or prolonged external faults.

Protection against internal faults in large transformers, as in generators, is usually obtained by percentage-differential relays. However, instead of simply comparing the current at one end of a winding with the current at the other end of the same winding, the relays compare the line currents in the high-voltage three-phase circuit to the transformer bank with the line currents in the low-voltage circuit. Under normal conditions or during external faults, these currents are unequal because of the transformation ratio of the protected transformer and sometimes also because of different connections on the two sides (for example, Y on one side and Δ on the other). Nevertheless, the currents actually compared by the relay, which are the secondary currents of current transformers, are made substantially equal under the above-mentioned conditions in the following manner: The transformation ratio is allowed for by using current transformers of different ratios on the two sides; and the difference in connections, by connecting the secondary windings of the current transformers in Y on the Δ-connected side of the power transformer and in Δ on the Y-connected side, as shown in Fig. 40. The reason for connecting the current transformers thus will be understood if it is noted that each line current on the Δ-connected side of the power transformer bank is the difference of the currents in two transformers, whereas the line current on the Y-connected side is the same as the current in one transformer. Consequently, the line current on the Δ side should be compared with the difference of two line currents on the Y side, obtainable by connecting the secondary windings of the current transformers in Δ.

Differential relays connected as described give protection against turn-to-turn faults, as well as against ground faults, phase-to-phase faults, and faults in the leads to the circuit breakers.

A three-winding transformer bank may be protected by use of percentage-differential relays having three restraining windings, one for each transformer winding, as shown by the single-line diagram in Fig. 41. The current in the operating winding of the relay is the vector sum of the current-transformer secondary currents representing the primary currents flowing toward the transformer in the line wires connected to the three windings.

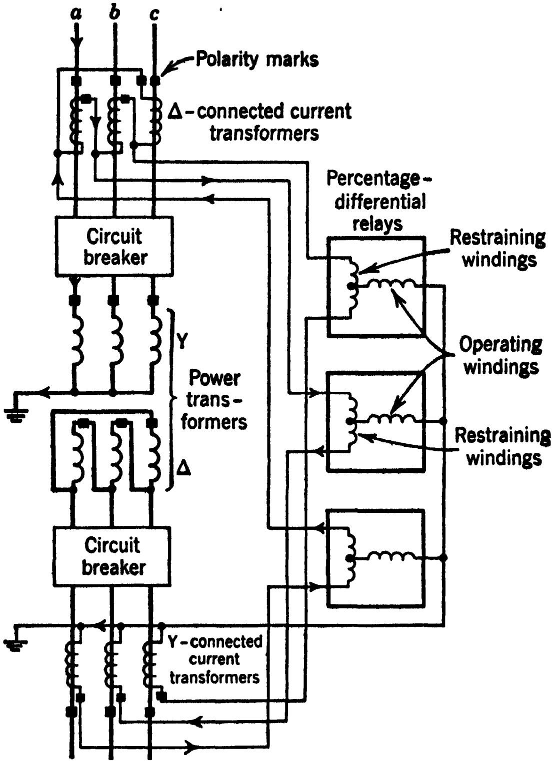


Fig. 40. Protection of a Y-Δ-connected bank of power transformers by percentage-differential relays. Note that the current transformers are connected in Δ on the Y side, and in Y on the Δ side. The windings of the power transformer have been drawn in a manner to facilitate comparison with the current-transformer connections. The arrowheads represent the paths of unit current resulting from an external fault from conductor *a* to ground on the Y side of the bank.

For several reasons, percentage-differential relays used for transformer protection cannot be set for as low a percentage difference as can relays used for generator protection: (1) Since the current transformers on the two sides of the power transformer have different ratios and voltage ratings, they cannot be as well matched as two transformers of the same ratio and type can be, and during external faults their ratios may depart unequally from the nominal values. (2) The ratio of transformation may be one which cannot be exactly compensated by the use of current transformers of standard ratios. (3) The ratio of some power transformers can be altered ±10% or more by changing taps, and it is not feasible to change taps on the current transformers correspondingly. For these reasons, the percentage difference for tripping is set at 25 to 50% of the smaller current, instead of at 10% as is usual for generator relays.

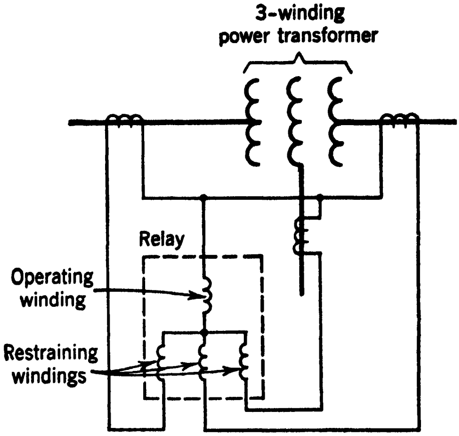


FIG. 41. Protection of a three-winding transformer by percentage-differential relays—single-line diagram.

When a transformer is first connected to a source of voltage, there is a transient *inrush of magnetizing current,* which may be as great as ten times full-load current and which may decay with a time constant as long as 2 sec. The magnitude of the inrush current varies with the point of the voltage wave at which the transformer is connected and with the polarity and magnitude of the residual magnetism in the transformer core. The decay of the inrush current is particularly slow if the primary winding of the transformer is directly in parallel with a winding of another transformer which is already in operation.[H8] There is a similar, but lesser, inrush when the voltage across a transformer recovers after the clearing of an external fault.

The magnetizing inrush tends to make differential relays operate falsely. A slow-speed induction-type differential relay is free from such trouble if it is given a long enough time setting. High-speed relays, which are sometimes required because of considerations of system stability, present a more serious problem in this respect. Three methods of preventing false operation have been employed—initial desensitization, harmonic restraint, and the use of a rectifier relay.

The first method decreases the sensitivity of the differential relays during a short time interval after closing the circuit breaker in the primary circuit. In order to disconnect the transformer if a fault develops in it when it is first excited, tripping is permitted during the initial time interval if there is not only a differential current but also a considerable decrease in voltage.

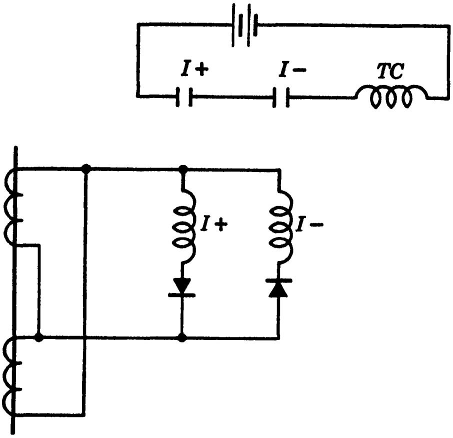


FIG. 42. Basic connections of rectifier relay. (Adapted from Ref. H22 by permission)

The *harmonic restraint relay*[H7] has an operating winding which carries only the fundamental-frequency current and a restraining winding which carries the d-c. and harmonic currents. Both the d-c. component and the harmonics are of large magnitude during the magnetizing inrush.

The *rectifier relay*[H22] utilizes the observed fact that the inrush current is a pulsating direct current of either positive or negative polarity, whereas fault current alternates. The basic circuit is shown in Fig. 42, where two relay coils are supplied with rectified current of opposite polarities, and both relays must close their contacts to trip the breaker. This basic circuit must be modified, however, to prevent false tripping during inrush because of the false alternating current which appears in the secondary circuit of the current transformers after a few cycles even when the primary current is pulsating direct current. In order to prevent tripping by the false alternating current, a time-delay relay *A* was added, as shown in Fig. 43. If both main relays $I+$ and $I-$ operate simultaneously or within 1.5 cycles, the trip circuit is closed. If, however, either of these relays is energized alone for 1.5

cycles or more, relay *A* operates and desensitizes the main relays by shunting their coils with resistor *R*. When the inrush current subsides to a value insufficient to cause tripping, relay *A* drops out and restores the sensitivity of the main relays.

The magnetizing inrush can be greatly reduced by switching the transformer onto the line through a circuit breaker having a series-resistance step.¶¶ Reduction of the inrush current lessens not only the relaying difficulty but also the dip in voltage.

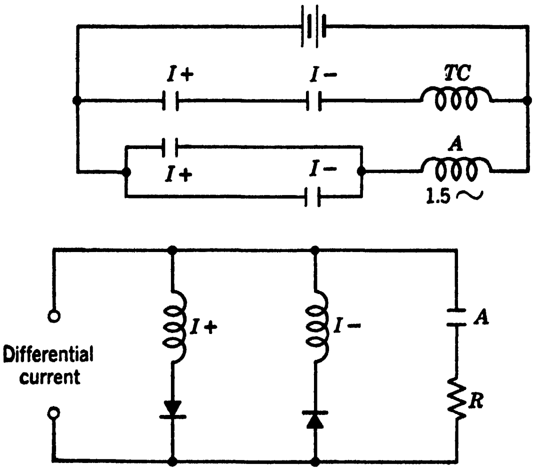


FIG. 43. Use of time-delay relay *A* for desensitizing main relays of rectifier relay. (Adapted from Ref. H22 by permission)

Another effective method of protecting transformers against internal faults is the *gas-actuated relay*, or *Buchholz relay*.H4, 28, 30, 31 Such relays have been widely used in Europe and in Canada, but they have not yet been extensively employed in the United States. They utilize the principle that a fault in an oil-insulated transformer decomposes oil or solid insulation, thereby generating gas. Incipient faults evolve gas very slowly, whereas severe faults quickly generate large quantities of gas and increase the pressure in the transformer tank. Gas-actuated relays have two elements: a sensitive element, actuated by slow accumulation of gas, which detects incipient faults and sounds an alarm, and a quick-acting element which responds to pressure or gas flow and trips the circuit breakers when a bad fault occurs.

¶¶Discussion of Ref. H8 by Eric T. B. Gross.

Gas-actuated relays are suitable for installation on oil-filled transformers having expansion tanks (conservators). One type is designed to be installed in the pipe line from the transformer tank to the conservator, as shown in Fig. 44*a*; the other, to be placed on the cover of the transformer tank, as shown in Fig. 44*b*. The mechanism of a relay of the pipe-line type is shown in Fig. 45. Gas collecting in the upper part of the cast housing lowers a hinged float *A*, closing a mercury switch *SA* which sounds an alarm. Rapid generation of gas by a severe fault produces enough flow of oil in the pipe to move the hinged flat *F*, which closes switch *S* and trips the circuit breakers. Slow movements of the oil which occur during normal heating and cooling do not actuate this element. A petcock *V* at the top of the gas-collecting chamber permits gas to be removed for analysis and for resetting the float. Another petcock *V* at the bottom of the relay permits testing of the relay by injection of air by a tire pump.

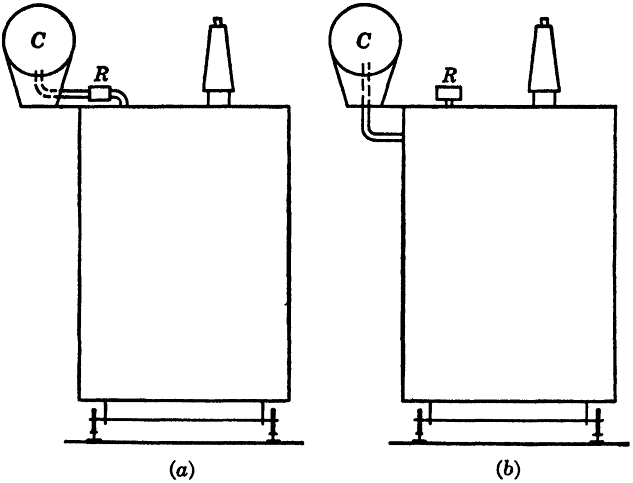


FIG. 44. Installation of gas-actuated relay *R* on transformer with conservator *C*. (*a*) In pipe line. (*b*) On cover of tank. (From Ref. H28 by permission)

The cover type of relay, shown in Fig. 46, differs from the pipe-line type chiefly in that the severe-fault element is operated by rapid increase of pressure instead of by rapid oil flow.

Operating experience has shown that transformer faults may be divided into two groups. The first group includes minor faults which actuate only the sensitive element of a gas-actuated relay and which could not be detected by any other type of protection now available. Among such faults are defective core-bolt insulation, short-circuited turns, and poor joints in conductors or in tap changers.[H30] The detection of such faults in their early stages makes it possible to repair them more quickly and cheaply and with less disruption of service than if they were allowed to develop into faults severe enough to be cleared by other kinds of protective relays. The second group of transformer faults comprises the severe ones which can be cleared satisfactorily either by the quick-acting element of a gas relay or by differential current relays.

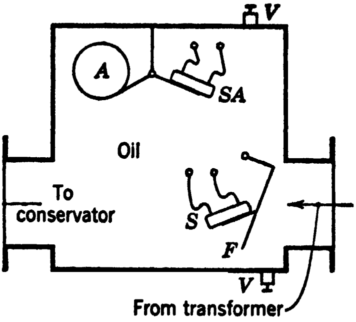


FIG. 45. Pipe-line-type gas-actuated relay in normal or "off" position. (From Ref. H28 by permission)

A	Float.
F	Flap.
SA	Alarm switch.
S	Severe-fault switch.
V	Valve.

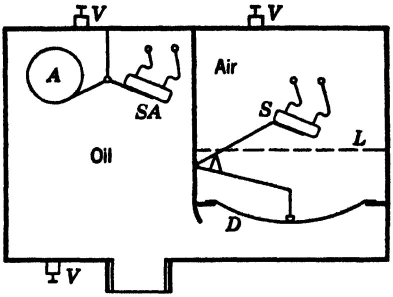


FIG. 46. Cover-type gas-actuated relay in normal or "off" position. (From Ref. H28 by permission)

A	Float.
D	Diaphragm.
SA	Alarm switch.
S	Severe-fault switch.
V	Valve.
L	Oil level in pressure chamber.

Gas relays are simpler than differential relays for protection of multicircuit transformers, rectifier transformers, and transformers with tap changers and are cheap enough to be used economically on instrument transformers and on small power transformers. They are not affected by magnetizing inrush currents. Gas relays respond only to faults inside the transformer tank, whereas the zone of protection of differential relays may include the transformer leads and circuit breakers.

If both windings of a two-winding transformer bank are connected to sources of power (because the protected transformer is operating in parallel with other transformers, for example), the differential or gas-pressure relays should trip the circuit breakers on both sides of the bank. Similarly, in a multiwinding transformer, breakers should be tripped at all terminals through which power could be fed to an internal fault.

Often a transformer is operated as an integral part of a transmission circuit, without a high-voltage circuit breaker. Clearing a fault in the transformer then requires opening the circuit breaker at the distant end of the line in addition to the local low-voltage breaker. Two ways in which the distant breaker can be tripped are: (1) transferred tripping by carrier current,[G18] and (2) the closing of a spring-actuated air-break grounding switch on the high-voltage side of the transformer.[B17] The grounding switch creates a short circuit, which is cleared by the relays and breaker at the far end of the line.

Overload protection may be given transformers by thermal relays or overcurrent relays. Thermal relays should respond to copper temperature, as indicated by core or oil temperature and by load current, instead of responding to core or oil temperature only. The reason is that the windings have a much shorter thermal time constant than the core and oil have.

Bus protection. The protected zone of a bus includes, besides the bus itself, such parts of the circuits branching from the bus as circuit breakers, disconnecting switches, and instrument transformers; it includes also bus-sectionalizing reactors and circuit breakers. Among the causes of bus faults are failures of circuit breakers to interrupt fault current, animals (cats, rats, etc.) getting into bus compartments, and mistakes made by operating personnel—for example, opening disconnecting switches under load. Bus faults are much less common than line faults, but they are considerably more disastrous in their effects. The clearing of a bus fault requires the opening of all the circuits branching from the faulted bus or bus section (except circuits having no back-feed) and, therefore, usually results in the disconnection of much generation or transmission capacity or both. Unless a bus fault is cleared rapidly, the damage at the fault may be so severe that extensive repairs will need to be made before service can be restored.

Some busses have no bus relays. Faults on such busses are cleared by time-delay back-up relays on the branch circuits. In order to minimize damage, however, a high-speed bus-relay system is desirable. In some instances, considerations of system stability require high-speed bus relaying.

There has been some unsatisfactory experience with bus relays tripping on external faults. Since external faults are much more frequent than bus faults, and since false tripping of a bus severely disrupts service, false tripping by bus relays cannot be tolerated. It is better to have no bus relays than unreliable ones.

The commonest form of bus protection is by *differential relaying.* In this scheme, current is supplied to the operating winding of the bus relay from the paralleled secondary windings of current transformers in all circuits branching from the bus (Fig. 47). All current transformers should have the same ratio. If the nominal ratios are maintained under all conditions, the relay current, which is the sum of the current-transformer secondary currents, will be proportional to the sum of the currents flowing into the bus on all circuits connected to the bus. This sum is zero except during an internal fault.

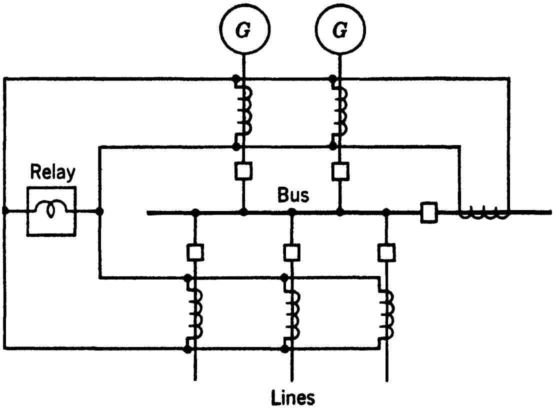


FIG. 47. Differential protection of a bus section.

It is not sufficient that the current transformers have equal ratios at equal currents, as it is in generator differential protection, where only two current transformers are used per phase.*** Since, during an external fault, the entire fault current goes out on one circuit but comes in on several circuits, the current-transformer ratios must be constant up to the maximum external-fault current. Otherwise there will be current in the relay operating winding during external faults.

The chief trouble with differential protection is failure of current transformers to maintain constant ratio when their cores are saturated by the d-c. component of short-circuit current. The d-c. component

---

***If the generator is connected to a double bus, so that there are two current transformers, one at each breaker, to be balanced against one current transformer at the neutral end of the generator winding, the requirements for current transformers may be as rigid as in the case of bus protection.

is especially troublesome, because of its slow decay, during faults at or near a generator bus.

It is not feasible to build current transformers with closed cores of sufficient cross-sectional area to avoid saturation due to d-c. transients with long time constants. Two special types of current transformers have been developed to avoid saturation, however: one having an air gap in the core;[110] the other, known as a *linear coupler*, having no iron core at all.[114] The secondary voltage of the linear coupler is proportional to the primary current, and the secondary windings of all couplers on the same bus section are connected in series to the relay.

Another frequent source of trouble with bus differential relays, in addition to current-transformer imperfections, is multiple grounding of interconnected current-transformer secondary windings, which either short-circuits relay coils or else permits stray ground-fault currents to enter the relays.[18] The remedy, of course, is to remove all ground connections except one.

Various schemes have been devised to prevent false operation of bus differential relays during external faults, in spite of imperfections of current transformers, by providing some kind of restraint. The percentage-differential relay, already mentioned in connection with generator and transformer protection, is applicable; but, in the case of a bus having many branch circuits, there is difficulty in providing a large enough number of restraining windings to ensure adequate restraint for every location of external fault. Harmonic restraint[13] is also applicable to bus protection, because the false differential current from saturated current transformers has a high harmonic content.

It has been found that, if the bus differential relay has a high impedance, it can discriminate between internal and external faults better than the usual low-impedance relay can. That is, the ratio of relay current during an internal fault to relay current during an external fault is greater the higher is the impedance of the relay. A scheme of bus differential protection using a high-impedance relay has been developed which operates satisfactorily without a restraint winding and with currents from bushing current transformers.[119]

Impedance or *reactance relays* have been used to protect some busses where current-limiting reactors were installed in the feeders and between bus sections. In one such scheme, the relay is supplied with potential from the bus potential transformers and with current from the paralleled current transformers of the incoming circuits (see Fig. 48). This relay trips the circuit breakers of all incoming circuits. The power-directional relay prevents operation on an external fault on one of these circuits. In another scheme, each incoming circuit has its own distance relays, which are supplied with current only from its own current transformers and which trip only its own circuit breaker.

Fault bus. Another kind of bus protection is the use of a ground-fault bus.[11] It is applicable to segregated-phase bus structures, where all faults necessarily involve ground. All metal parts, such as insulator supports, oil-switch tanks, and structural members, are grounded only in one place in each bus section, through the winding of an overcurrent relay which trips the breakers of all circuits on its own bus section. The use of a ground-fault bus necessitates careful construction of the switch-house to prevent connections between the reinforcing steel of two different bus sections, which would result in a fault on one section tripping both sections.

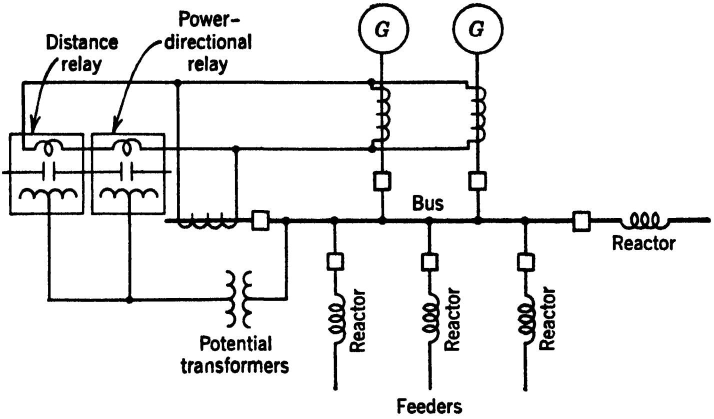


FIG. 48. Bus protection by use of distance and power-directional relays.

REFERENCES

A. Protective Relaying—General

1. Trade literature of the General Electric Co., Schenectady, N. Y., and of the Westinghouse Electric Corporation, East Pittsburgh, Pa.

2. REINHOLD RÜDENBERG (editor), *Relais und Schutzschaltungen in elektrischen Kraftwerken und Netzen* (*Relays and Protective Circuits in Electric Power Stations and Networks*), Berlin, Julius Springer, 1929, 281 pp.

3. FRITZ KESSELRING, *Selektivschutz* (*Selective Protection*), Berlin, Julius Springer, 1930, 181 pp.

4. *Relay Handbook and Supplement*, Publication 142, National Electric Light Association, New York, 1931.

5. I. T. MONSETH and P. H. ROBINSON, *Relay Systems—Theory and Application*, New York, McGraw-Hill Book Co., 1935.

6. ROBERT TREAT, "Factors in Making Electrical Power Supply Dependable," *Gen. Elec. Rev.*, vol. 38, pp. 376–83, August, 1935.

7. P. F. Stritzl, *Protection of Electric Plant: Modern Developments*, London, Sir Isaac Pitman & Sons, 1936.

8. Manfred Schleicher (editor), *Die moderne Selektivschutztechnik und die Methoden zur Fehlerortung in Hochspannungsanlagen* (*Modern Protective Relaying and the Methods of Locating Faults in High-Voltage Systems*), Berlin, Julius Springer, 1936; and Ann Arbor, Mich., J. W. Edwards, 1944.

9. *The Art of Protective Relaying*, Publication GEA-2558, General Electric Co., Schenectady, N. Y., 1939; GEA-2558A, 1947.

10. Relay Subcommittee of the A.I.E.E. Committee on Protective Devices, "High-Speed-Relaying Experience and Practice," *A.I.E.E. Trans.*, vol. 58, pp. 588–91, November, 1939. Disc., pp. 591–2.

11. *Silent Sentinels: Westinghouse Protective Relays*, Publication TD 41-000, Westinghouse Electric Corporation, 1949.

12. A. R. van C. Warrington, "A Condensation of the Theory of Relays," *Gen. Elec. Rev.*, vol. 43, pp. 370–3, September, 1940.

13. Relay Subcommittee of the A.I.E.E. Committee on Protective Devices, "Bibliography of Relay Literature, 1927–1939," *A.I.E.E. Trans.*, vol. 60, pp. 1435–47, 1941.

14. E. L. Harder and J. C. Cunningham, "Relay and Circuit-Breaker Application," Chap. 10 of *Electrical Transmission and Distribution Reference Book* by Central Station Engineers of the Westinghouse Electric & Manufacturing Co., East Pittsburgh, 1st edition, 1942; 3rd edition, 1944.

15. G. W. Stubbings, *Automatic Protection of A-C Circuits*, London, Chapman & Hall, Ltd., 3rd edition, 1943.

16. Relay Subcommittee of the A.I.E.E. Committee on Protective Devices, "Bibliography of Relay Literature, 1940–1943," *A.I.E.E. Trans.*, vol. 63, pp. 705–9, October, 1944.

17. *Principles of System Relaying*, a report of the Electrical Equipment Committee, Edison Electric Institute, New York, Publication M-3, July, 1945.

18. E. W. Knapp and Ben C. Hicks, "Philosophy of Relaying," *A.I.E.E. Trans.*, vol. 65, pp. 735–41, November, 1946. Disc., p. 1135.

19. Lloyd F. Hunt, "Simplicity in Protective Relaying," *A.I.E.E. Trans.*, vol. 65, pp. 995–1000, 1946. Disc., pp. 1121–3.

20. A.I.E.E. Relay Committee, "Bibliography of Relay Literature 1944–1946," *A.I.E.E. Trans.*, vol. 67, part I, pp. 24–7, 1948.

21. E. L. Harder and W. E. Marter, "Principles and Practices of Relaying in the United States," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1005–22, 1948. Disc., pp. 1022–3.

B. Line Protection—General

1. W. W. Edson, "Transmission System Relay Protection—III," *A.I.E.E. Trans.*, vol. 49, pp. 1213–24, October, 1930. Disc., pp. 1224–5.

2. O. C. Traver and L. F. Kennedy, "Modern Requirements for Protective Relays on Important System Interconnections," *A.I.E.E. Trans.*, vol. 49, pp. 1226–31, October, 1930. Disc., pp. 1239–42.

3. L. N. Crichton, "High-Speed Protective Relays," *A.I.E.E. Trans.*, vol. 49, pp. 1232–9, October, 1930. Disc., pp. 1239–42.

4. T. G. LeClair, "Relay Protection for a 'Close-Linked' System," *Elec. Eng.*, vol. 50, pp. 471–5, July, 1931.

5. S. L. Goldsborough and R. M. Smith, "A New Overcurrent Relay—Has

Adjustable Straight-Line Characteristics," *Elec. Jour.*, vol. 29, pp. 78–80, February, 1932.

6. G. W. Gerell, "Application of High-Speed Relays" (to 66- and 132-Kv. System of Union Electric Light and Power Company) (abstract), *Elec. Eng.*, vol. 51, p. 411, June, 1932.

7. R. C. Erickson, "Relaying in Chicago Region," *Elec. Light and Power*, vol. 10, no. 11, pp. 10–2, November, 1932.

8. H. P. Sleeper, "Relaying of High-Voltage Interconnections," *Elec. Eng.*, vol. 52, pp. 402–9, June, 1933.

9. C. H. Frier, "Instantaneous Overcurrent Relays for Distance Relaying," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 54, pp. 404–7, April, 1935. Disc., pp. 883–4, August, 1935.

10. W. A. Lewis, "Operation of High-Speed Relays," *Elec. Jour.*, vol. 32, pp. 446, 448, October, 1935.

11. C. A. Muller and H. E. Turner, "Modernization of Relay Systems," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 56–62, January, 1936. Disc., pp. 922–5, August, 1936.

12. G. W. Gerell, "Experiences with a Modern Relay System," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 1130–6, October, 1936. Disc., vol. 56, pp. 369–70, March, 1937.

13. L. L. Draper, "Symposium on Operation of the Boulder Dam Transmission Line—Transmission Line Relay Protection," *A.I.E.E. Trans.*, vol. 58, pp. 151–6, April, 1939. Disc., pp. 156–60.

14. C. R. Mason, "Relay Protection of A-C. Rotating Machines, Transformers, Buses, and Lines. Part III: Lines," *Gen. Elec. Rev.*, vol. 42, pp. 529–39, December, 1939.

15. J. W. Gallop and R. H. Bousfield, "Applications and Limitations of Inverse-Time Overload Relay to Protection of 11-Kv. Network," *I.E.E. Jour.* (London), vol. 87, pp. 113–29, August, 1940. Disc., pp. 129–34.

16. W. A. Lewis, "High-Speed Relaying," *Proc. Midwest Power Conference* (Chicago), vol. 5, pp. 137–55, 1942.

17. A. R. van C. Warrington, "Protective Relaying for Long Transmission Lines," *A.I.E.E. Trans.*, vol. 62, pp. 261–8, June, 1943. Disc., p. 427.

18. F. C. Poage, C. A. Streifus, D. M. MacGregor, and E. E. George, "Performance Requirements for Relays on Unusually Long Transmission Lines," *A.I.E.E. Trans.*, vol. 62, pp. 275–83, June, 1943. Disc., pp. 422–5.

19. C. W. Minard, R. B. Gow, W. A. Wolfe, and E. A. Swanson, "Staged-Fault Tests of Relaying and Stability on Kansas–Nebraska 270-Mile 154-Kv Interconnection," *A.I.E.E. Trans.*, vol. 62, pp. 358–67, 1943. Disc., pp. 425–6.

20. M. A. Bostwick and E. L. Harder, "Protection of Three-Terminal Lines," *Westinghouse Engineer*, vol. 3, pp. 76–9, August, 1943.

21. W. A. Lewis, "The Principles of High-Speed Relaying," *Westinghouse Engineer*, vol. 3, pp. 91–4, August, 1943; pp. 131–4, November, 1943.

22. V. N. Stewart, "A New High-Speed Balanced-Current Relay," *A.I.E.E. Trans.*, vol. 62, pp. 553–5, August, 1943. Disc., pp. 972–4.

23. M. A. Bostwick and E. L. Harder, "Relay Protection of Tapped Transmission Lines," *A.I.E.E. Trans.*, vol. 62, pp. 645–50, October, 1943. Disc., pp. 969–72.

C. Directional Relays

1. A. J. McConnell, "A Single-Element Polyphase Directional Relay," *A.I.E.E. Trans.*, vol. 56, pp. 77–80, January, 1937. Disc., pp. 1025–8, August, 1937.

2. Bert V. Hoard, "An Improved Polyphase Directional Relay," *A.I.E.E. Trans.*, vol. 60, pp. 246–8, May, 1941. Disc., pp. 681–3.

3. Troy D. Graybeal, "Factors Which Influence the Behavior of Directional Relays," *A.I.E.E. Trans.*, vol. 61, pp. 942–52, 1942.

4. W. C. Morris, "A New One-Cycle Directional Overcurrent Relay," *A.I.E.E. Trans.*, vol. 62, pp. 725–7, November, 1943. Disc., pp. 989–91.

5. W. C. Morris, "Directional Overcurrent Relay," *Gen. Elec. Rev.*, vol. 46, pp. 571–4, October, 1943.

D. Line Protection—Distance

1. Leslie N. Crichton, "The Distance Relay for Automatically Sectionalizing Electrical Networks," *A.I.E.E. Trans.*, vol. 42, pp. 527–32, April, 1923. Disc., pp. 532–7. Also in *A.I.E.E. Jour.*, vol. 42, pp. 793–8, August, 1923.

2. S. L. Goldsborough, "The Distance Relay," *Elec. Jour.*, vol. 20, pp. 154–9, May, 1923. Type CZ.

3. John V. Breisky and H. A. McLaughlin, "Developments in the Impedance-Type Relay," *Elec. Jour.*, vol. 24, pp. 80–4, February, 1927.

4. Paul Ackerman, "A Study of Transmission Line Power Arcs," *Eng. Jour.* (Montreal), vol. 11, pp. 309–23, May, 1928. Disc., p. 504, September, 1928.

5. H. A. McLaughlin and E. O. Erickson, "The Impedance Relay—Developments and Application," *A.I.E.E. Trans.*, vol. 47, pp. 776–82, July, 1928. Disc., pp. 782–4.

6. J. Fallou, "Sur l'emploi des relais d'impédance pour la protection des lignes aériennes contre les mises à la terre (On the Use of Impedance Relays for the Protection of Overhead Lines against Ground Faults)," *Bull. de la Société Française des Électriciens*, series 4, vol. 10, pp. 82–94, 1930.

7*a*. H. S. [should be S. L.] Goldsborough, "High-Speed Relays Increase System Stability," *Elec. Jour.*, vol. 27, pp. 400–1, July, 1930. Type HZ.

7*b*. L. N. Crichton, "High-Speed Protective Relays," *A.I.E.E. Trans.*, vol. 49, pp. 1232–9, October, 1930. Disc., pp. 1239–42.

8. E. E. George, "Operating Experience with Reactance Type Distance Relays," *A.I.E.E. Trans.*, vol. 50, pp. 288–93, March, 1931. Disc., p. 293.

9. W. A. Lewis and L. S. Tippett, "Fundamental Basis for Distance Relaying on Three-Phase Systems," *A.I.E.E. Paper* 31-61. Abstract, *Elec. Eng.*, vol. 50, pp. 420–2, June, 1931. See also Ref. D36.

10. E. Gross, "Schaltungen für Distanzrelais (Connections for Distance Relays)," *V.D.E. Fachberichte*, pp. 88–91, 1931. Disc., p. 91.

11. E. Gross, "Protection sélective dans les réseaux haute tension avec neutre mis directement à la terre (Protective Relaying in High-Voltage Networks with Solidly Grounded Neutral)," *Congrès International d'Électricité*, Paris, 1932, 4e Section, Communication no. 15-C.

12. S. L. Goldsborough and W. A. Lewis, "A New High-Speed Distance Relay," *A.I.E.E. Paper* 32M1, January, 1932. Abstract, *Elec. Eng.*, vol. 51, pp. 157–60, March, 1932. Beam-type relay with modified impedance characteristic.

13. M. Walter, "Die Distanzschutzschaltungen (Distance-Relay Connec-

tions)," *Elektrizitaetswirtschaft* (Berlin), vol. 31, pp. 172–6, April 30, 1932, and pp. 199–202, May 15, 1932.

14. M. Walter, "Der Kurzschluss-Lichtbogen in Drehstromnetzen und sein Einfluss auf die Arbeitsweise der Distanzrelais (The Short-Circuit Arc in Three-Phase Systems and Its Influence on the Operation of Distance Relays)," *E.T.Z.* (Berlin), vol. 53, pp. 1056–9, November 3, 1932.

15. M. Walter, *Der Selektivschutz nach dem Widerstandsprinzip (Selective Protection by the Impedance Principle)*, München, R. Oldenbourg, 1933.

16. A. R. van C. Warrington, "A High-Speed Reactance Relay," *A.I.E.E. Paper* 32M12, June, 1932. Abstract, *Elec. Eng.*, vol. 52, pp. 248–52, April, 1933.

17. F. Fröhlich and G. Stark, "AEG-Schnelldistanzschutz (A.E.G. High-Speed Distance Protection)," *A.E.G. Mitteilungen*, vol. (1934), pp. 27–31, January, 1934.

18. A. R. van C. Warrington, "Control of Distance Relay Potential Connections," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 206–13, January, 1934. Disc., pp. 465–6, March; p. 617, April, 1934.

19. E. Gross, "Die neuere Entwicklung der Distanzschutzschaltungen (New Developments in Distance Relay Connections)," *Elektrotechnik und Maschinenbau* (Vienna), vol. 52, pp. 597–602, Dec. 23, 1934, and pp. 612–6, Dec. 30, 1934.

20. L. N. Crichton, "A High-Speed Distance Relay," *Elec. Jour.*, vol. 32, pp. 537–42, December, 1935. Type HCZ.

21. Giuseppe Calabrese, "Performance of Distance Relays," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 660–72, June, 1936. Disc., pp. 1254–5, November, 1936. Effect of Δ–Y or Y–Δ transformers.

22. S. L. Goldsborough and R. M. Smith, "A New Distance Ground Relay," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 697–703, June, 1936. Disc., pp. 1255–6, November, 1936.

23. J. H. Neher, "A Comprehensive Method of Determining the Performance of Distance Relays," *A.I.E.E. Trans.*, vol. 56, pp. 833–44, July, 1937. Disc., p. 1515, December, 1937.

24. Gerhard Walther, "Übersicht über Distanzschutzeinrichtungen (Review of Distance-Relay Equipment)," *E.T.Z* (Berlin), vol. 61, part 1, pp. 85–8, January 25, 1940.

25. [A. R. van C. Warrington], "Interesting Facts about Power Arcs," *Relaying News* (General Electric Co., Schenectady, N. Y.), no. 20, pp. 1–2, January, 1941.

26. J. L. Blackburn, "Distance Relaying with Low-Tension Potentials," *Westinghouse Engineer*, vol. 3, pp. 61–4, May, 1943.

27. L. J. Audlin and A. R. van C. Warrington, "Distance Relay Protection for Subtransmission Lines Made Economical," *A.I.E.E. Trans.*, vol. 62, pp. 574–8, September, 1943. Disc., pp. 976–9.

28. Erik Floor, H. N. Muller, Jr., and S. L. Goldsborough, "Transmission and Relaying Problems on the Fort Peck Project," *A.I.E.E. Trans.*, vol. 63, pp. 209–14, May, 1944. Disc., pp. 466–7.

29. J. L. Blackburn, "Compensators for Distance Relaying," *Elec. Wld.*, vol. 122, no. 4, pp. 146, 148, 150, July 22, 1944; no. 8, pp. 112–3, August 19, 1944; and no. 12, p. 112, Sept. 16, 1944.

30. S. L. Goldsborough, "A Distance Relay with Adjustable Phase-Angle Discrimination," *A.I.E.E. Trans.*, vol. 63, pp. 835–8, November, 1944. Disc., pp. 1471–2.

31. A. P. STROM, "Long 60-Cycle Arcs in Air," *A.I.E.E. Trans.*, vol. 65, pp. 113–8, March, 1946. Disc., pp. 504–7.

32. R. M. HUTCHINSON, "The Mho Distance Relay," *A.I.E.E. Trans.*, vol. 65, pp. 353–60, June, 1946.

33. A. R. VAN C. WARRINGTON, "Application of the Ohm and Mho Principles to Protective Relays," *A.I.E.E. Trans.*, vol. 65, pp. 378–86, June, 1946. Disc., pp. 490–1.

34. W. A. WOLFE, "Operating Experience with Distance Ground Relays," *A.I.E.E. Trans.*, vol. 65, pp. 458–62, July, 1946. Disc., pp. 1185–7.

35. H. LEYBURN and C. H. LACKEY, "Some Recent Developments in the Protection of E.H.V. Overhead-Line Networks," *C.I.G.R.E.*, 1946, vol. 3, report 338, 26 pp.

36. W. A. LEWIS and L. S. TIPPETT, "Fundamental Basis for Distance Relaying on 3-Phase Systems," *A.I.E.E. Trans.*, vol. 66, pp. 694–708, 1947. Disc., pp. 708–9. See Ref. D9.

37. C. G. DEWEY and J. R. McGLYNN, "A New Reactance Distance Relay," *A.I.E.E. Trans.*, vol. 67, part I, pp. 743–6, 1948. Disc., p. 746.

38. S. L. GOLDSBOROUGH, "A New Distance Ground Relay," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1442–6, 1948. Disc., pp. 1446–7.

39. R. H. MACPHERSON, A. R. VAN C. WARRINGTON, and A. J. McCONNELL, "Electronic Protective Relays," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1702–7, 1948. Disc., pp. 1707–8. Also in *Elec. Eng.*, vol. 68, pp. 122–8, February, 1949. Electronic mho relay.

40. A. R. VAN C. WARRINGTON, "Graphical Method for Estimating the Performance of Distance Relays During Faults and Power Swings," *A.I.E.E. Trans.*, vol. 68, part I, pp. 608–20. Disc., pp. 620–1.

E. Line Protection—Ground Faults

1. E. E. GEORGE and R. H. BENNETT, JR., "Directional Ground Relays," *A.I.E.E. Trans.*, vol. 49, pp. 1243–54, October, 1930. Disc., pp. 1254–5.

2. F. M. STARR, "A New Method of Ground Fault Protection," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 1472–7, November, 1934.

3. S. L. GOLDSBOROUGH and R. M. SMITH, "A New Distance Ground Relay," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 697–703, June, 1936. Disc., pp. 1255–6, November, 1936.

4. B. V. HOARD and S. C. LEYLAND, "Directional Overcurrent Ground Relaying," *Elec. Jour.*, vol. 36, pp. 97–101, March, 1939. Type CRS relay having a negative-sequence directional element.

5. E. H. BANCKER, "Induced Current in Parallel Circuits and Its Effect Upon Relays," *A.I.E.E. Trans.*, vol. 58, pp. 582–5, November, 1939. Disc., pp. 585–8.

6. ERIC T. B. GROSS, "Sensitive Ground Protection for Transmission Lines and Distribution Feeders," *A.I.E.E. Trans.*, vol. 60, pp. 968–71, November, 1941.

7. W. K. SONNEMANN, "A New Single-Phase-to-Ground Fault-Detecting Relay," *A.I.E.E. Trans.*, vol. 61, pp. 677–80, September, 1942. Disc., pp. 995–6.

8. R. B. SQUIRES, "Filter Bans 25-Cycle from Ground Relay," *Elec. Wld.*, vol. 119, no. 26, p. 88 (2164), June 26, 1943.

9. JOHN I. HOLBECK and MARTIN J. LANTZ, "The Effects of Mutual Induction between Parallel Transmission Lines on Current Flow to Ground Faults," *A.I.E.E. Trans.*, vol. 62, pp. 712–5, November, 1943. Disc., pp. 1002–3.

10. K. I. BROWN, "Automatic Selective Isolation of Sustained Earth Faults on

a Network Protected by Petersen Coils," *I.E.E. Jour.*, vol. 91, part 2, pp. 21–7, February, 1944. Disc., pp. 27–34.

11. L. B. S. Golds and C. L. Lipman, "A Modern Earth-Fault Relay Equipment for Use on Systems Protected by Petersen Coils," *I.E.E. Jour.*, vol. 91, part 2, pp. 377–88, October, 1944. Disc., pp. 389–96. Abstract of discussion in *Electrician* (London), vol. 132, pp. 169–70, February 25, 1944; *Elec. Times*, vol. 105, pp. 226–7, February 24, 1944; and in *Elec. Rev.* (London), vol. 134, p. 234, February, 18, 1944.

12. A. R. Curry, "Lockout Relays Deter Possible Outages," *Elec. Wld.*, vol. 123, p. 76, March 3, 1945.

13. W. A. Wolfe, "Operating Experience with Distance Ground Relays," *A.I.E.E. Trans.*, vol. 65, pp. 458–62, July, 1946. Disc., pp. 1185–7.

14. Lloyd F. Hunt, "Sensitive Ground Relay Protection for Complex Distribution Circuits," *A.I.E.E. Trans.*, vol. 65, pp. 765–8, November, 1946. Disc., pp. 1180–1.

F. Line Protection—Pilot Wire

1. R. F. Schuchardt, "The Protective Equipment on the System of the Commonwealth Edison Company," *A.I.E.E. Trans.*, vol. 36, pp. 377–89, 1917. Disc., pp. 390–416.

2. C. H. Frier, "Relaying with Two Pilot Wires," *Elec. Eng.*, vol. 50, pp. 824–6, October, 1931.

3. G. M. Babcock, "Supervisory Pilot-Wire Relaying—Modified Form of Pilot-Wire Relay Circuit to Eliminate Cascaded Timing in Transmission-Line Protection," *Elec. West*, vol. 68, pp. 337–9, May 15, 1932.

4. C. M. Longfield, "D.C. Pilot Wire Systems of Relay Protection," *Metropolitan-Vickers Gazette* (Manchester), vol. 13, pp. 417–22, December, 1932.

5. J. H. Neher, "D.C. Pilot-Wire Loop Protects 66-Kv. Cable Circuits," *Elec. Wld.*, vol. 101, pp. 384–7, March 25, 1933.

6. J. H. Neher, "The Use of Communication Facilities in Transmission-Line Relaying," *A.I.E.E. Trans.*, vol. 52, pp. 595–602, June, 1933. Disc., pp. 603–6.

7. E. E. George and W. R. Brownlee, "Pilot Wire Relay Protection," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 54, pp. 1262–9, November, 1935. Disc., vol. 55, pp. 907–9, August, 1936.

8. Lloyd F. Hunt, "New Pilot Protection Gives Reliability," *Elec. Wld.*, vol. 106, pp. 43–5 (3007–9), September 26, 1936.

9. E. L. Harder and M. A. Bostwick, "A Single-Element Differential Pilot-Wire Relay System," *Elec. Jour.*, vol. 35, pp. 443–8, November, 1938.

10. J. H. Neher and A. J. McConnell, "An Improved A-C Pilot-Wire Relay," *A.I.E.E. Trans.*, vol. 60, pp. 12–7, January, 1941. Disc., pp. 638–43.

11. E. L. Harder and M. A. Bostwick, "Protection of Pilot-Wire Circuits," *A.I.E.E. Trans.*, vol. 61, pp. 645–52, September, 1942. Disc., pp. 996–8.

12. A.I.E.E. Committee on Protective Devices, "Pilot-Wire Circuits for Protective Relaying—Experience and Practice," *A.I.E.E. Trans.*, vol. 62, pp. 210–4, May, 1943. Disc., pp. 380–1.

13. T. G. LeClair and E. L. Michelson, "Pilot-Wire Relaying on a Metropolitan System," *A.I.E.E. Trans.*, vol. 62, pp. 511–5, August, 1943. Disc., pp. 974–6.

14. R. B. Killen and G. G. Law, "Protection of Pilot Wires from Induced Potentials," *A.I.E.E. Trans.*, vol. 65, pp. 267–70, May, 1946.

G. Line Protection—Carrier Current

1. PHILIP SPORN and CHARLES A. MULLER, "Carrier-Current Relaying Proves Its Effectiveness," *Elec. Wld.*, vol. 100, pp. 332–6, September 10, 1932.

2. OLIVER C. TRAVER, JOHN AUCHINCLOSS, and ELBERT H. BANCKER, "Pilot Protection by Power-directional Relays Using Carrier Current," *Gen. Elec. Rev.*, vol. 35, pp. 566–70, November, 1932.

3. PHILIP SPORN and CHARLES A. MULLER, "Carrier-Current Relaying Simplified," *Elec. Wld.*, vol. 102, pp. 556–60, October 28, 1933.

4. O. A. BROWNE and W. L. VEST, JR., "A Carrier Current Relay Installation," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 54, pp. 109–15, January, 1935. Disc., pp. 333–4, March; pp. 558–9, May, 1935.

5. PHILIP SPORN and C. A. MULLER, "One-Cycle Carrier Relaying Accomplished," *Elec. Wld.*, vol. 105, no. 21, pp. 26–8 (2434–6), October 12, 1935.

6. M. E. REAGAN, "Uses of Carrier Current," *Elec. Jour.*, vol. 33, pp. 276–9, June, 1936.

7. O. C. TRAVER and E. H. BANCKER, "A Faster Carrier Pilot Relay System," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 688–96, June, 1936. Disc., pp. 1252–4, November, 1936.

8. R. E. PIERCE, R. E. POWERS, E. C. STEWART, and G. E. HEBERLEIN, "Carrier Relaying and Rapid Reclosing at 110 Kv," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 1120–9, October, 1936.

9. A. R. WARRINGTON, "Carrier Pilot Relaying with Distance Backup," *Relaying News* (General Electric Co., Schenectady, N. Y.), no. 7, p. 17, June, 1937.

10. E. L. HARDER, B. E. LENEHAN, and S. L. GOLDSBOROUGH, "A New High-Speed Distance-Type Carrier-Pilot Relay System," *A.I.E.E. Trans.*, vol. 57, pp. 5–10, January, 1938. Disc., pp. 291–4, May, 1938.

11. PHILIP SPORN and CHARLES A. MULLER, "The Application and Performance of Carrier-Current Relaying," *A.I.E.E. Trans.*, vol. 57, pp. 118–24, March, 1938. Disc., pp. 281–4, May, 1938.

12. J. D. LAUGHLIN, "Symposium on Operation of the Boulder Dam Transmission Line—Carrier-Current Equipment," *A.I.E.E. Trans.*, vol. 58, pp. 147–51, April, 1939. Disc., pp. 156–60.

13. J. D. LAUGHLIN, W. E. PAKALA, and M. E. REAGAN, "Carrier-Current Losses Measured and Interference Minimized on Boulder–Los Angeles Transmission Lines," *A.I.E.E. Trans.*, vol. 59, pp. 4–9, January, 1940. Disc., pp. 9–10.

14. R. M. SMITH and S. L. GOLDSBOROUGH, "Possibilities and Methods of Extending a Carrier Current Relay Channel to Other Uses," *A.I.E.E. Trans.*, vol. 60, pp. 23–7, January, 1941. Disc., pp. 645–6.

15. H. E. WULFING and T. G. LECLAIR, "Powerton-Crawford 220-Kv. Line—System Operating Features and Terminal Design," *A.I.E.E. Trans.*, vol. 60, pp. 1084–9, 1941. Disc., p. 1304.

16. P. N. SANDSTROM and G. E. FOSTER, "Multichannel Carrier-Current Facilities for a Power Line," *A.I.E.E. Trans.*, vol. 61, pp. 71–6, February, 1942. Disc., p. 469.

17. M. STEPHENS MERRITT and T. DEWITT TALMAGE, "Carrier-Current Relaying and Communication on the TVA System," *Elec. Eng.*, vol. 61, pp. 561–72, November, 1942.

18. T. A. CRAMER, "Carrier-Current Differential Protection for Transformer Banks," *A.I.E.E. Trans.*, vol. 62, pp. 545–8, August, 1943. Disc., pp. 947–8.

19. E. M. Wood, H. W. Haberl, and F. A. A. Baily, "A New-Type Carrier Relay Protection," *A.I.E.E. Trans.*, vol. 62, pp. 774–9, December, 1943. Disc., pp. 986–8.

20. S. C. Leyland and S. L. Goldsborough, "The Functions of Ground Preference in Carrier-Current Relay Schemes," *A.I.E.E. Trans.*, vol. 63, pp. 97–100, March, 1944. Disc., p. 437.

21. H. W. Lensner and J. B. Singel, "A Versatile Power-Line-Carrier System," *A.I.E.E. Trans.*, vol. 63, pp. 129–33, March, 1944. Disc., pp. 437–9.

22. J. T. Logan, "Fault Current Polarities Compared by Carrier," *Elec. Wld.*, vol. 121, no. 16, pp. 84–5 (1408–9), April 15, 1944. Phase comparison.

23. S. C. Leyland, "One Carrier Relay for 'Phase and Ground,'" *Elec. Wld.*, vol. 121, no. 20, pp. 128, 130 (1808, 1810), May 13, 1944.

24. R. E. Cordray and A. R. van C. Warrington, "The Mho-Carrier Relaying Scheme," *A.I.E.E. Trans.*, vol. 63, pp. 228–35, May, 1944. Disc., pp. 434–6.

25. T. R. Halman, S. L. Goldsborough, H. W. Lensner, and A. F. Drompp, "A New Carrier Relaying System," *A.I.E.E. Trans.*, vol. 63, pp. 568–72, August, 1944. Disc., pp. 1423–6. Phase comparison.

26. R. C. Cheek, "A Comparison of the Amplitude-Modulation, Frequency-Modulation, and Single-Side-Band Systems for Power-Line Carrier Transmission," *A.I.E.E. Trans.*, vol. 64, pp. 215–20, May, 1945. Disc., pp. 450–2.

27. R. C. Cheek and W. A. Derr, "The Combination of Supervisory Control with Other Functions on Power-Line Carrier Channels," *A.I.E.E. Trans.*, vol. 64, pp. 241–6, May, 1945.

28. M. J. Brown, "Power-Line Carrier Channels," *A.I.E.E. Trans.*, vol. 64, pp. 246–51, May, 1945.

29. A. J. McConnell, T. A. Cramer, and H. T. Seeley, "Phase-Comparison Carrier-Current Relaying," *A.I.E.E. Trans.*, vol. 64, pp. 825–33, December, 1945. Disc., pp. 973–5.

30. Åke T. Vrethem and Gunnar Jancke, "Selective Protective Relay Equipment for High-Voltage Systems with Long Overhead Transmission Lines," *C.I.G.R.E.*, 1946, vol. 3, report 327, 28 pp. Protection of 220-kv. network in Sweden.

31. H. Leyburn and C. H. Lackey, "Some Recent Developments in the Protection of E.H.V. Overhead-Line Networks," *C.I.G.R.E.*, 1946, vol. 3, report 338, 26 pp. Phase-comparison scheme.

32. W. A. Morgan and Byron Evans, "Relaying Difficulties Disclosed by Staged-Fault Tests," *A.I.E.E. Trans.*, vol. 67, part I, pp. 73–82, 1948.

33. H. Touly, "Electronic Selective Protection," *C.I.G.R.E.*, report 316, 1948. Phase-comparison scheme with phase selector for single-pole tripping.

H. Apparatus Protection

1. R. E. Cordray, "Percentage-Differential Transformer Protection," *Elec. Eng.*, vol. 50, pp. 361–3, May, 1931.

2. Relay Subcommittee of the A.I.E.E. Committee on Protective Devices, "Protection of Electrical Apparatus—Recommended Practice," *A.I.E.E. Trans.*, vol. 52, pp. 607–13, June, 1933. Disc., p. 613.

3. "Notable Features of the Boulder Dam–Los Angeles Power System—Generator and Transformer Relaying," *Elec. Jour.*, vol. 33, p. 492, November, 1936.

4. R. A. Hentz, "Gas-Pressure Relays," *Edison Elec. Inst. Bull.*, vol. 6, pp. 82–4, March, 1938.

5. C. R. Mason, "Relay Protection of A-C Rotating Machines, Transformers,

Buses, and Lines. Part I: A-C Rotating Machines," *Gen. Elec. Rev.*, vol. 42, pp. 441–9, October, 1939; "Part II: Transformers and A-C Buses," *Gen. Elec. Rev.*, vol. 42, pp. 488–96, November, 1939.

6. W. K. Sonnemann, "A High-Speed Differential Relay for Generator Protection," *A.I.E.E. Trans.*, vol. 59, pp. 608–12, November, 1940. Disc., pp.1250–2.

7. C. D. Hayward, "Harmonic-Current-Restrained Relays for Transformer Differential Protection," *A.I.E.E. Trans.*, vol. 60, pp. 377–82, 1941. Disc., pp. 622–4.

8. C. D. Hayward, "Prolonged Inrush Currents with Parallel Transformers Affect Differential Relaying," *A.I.E.E. Trans.*, vol. 60, pp. 1096–101, 1941. Disc., pp. 1305–8.

9. G. C. Crossman, H. F. Lindemuth, and R. L. Webb, "Loss-of-Field Protection for Generators," *A.I.E.E. Trans.*, vol. 61, pp. 261–6, May, 1942. Disc., pp. 462–3.

10. P. W. Shill, "A Practical Discussion of Problems in Transformer Differential Protection," *A.I.E.E. Trans.*, vol. 61, pp. 854–8, December, 1942. Disc., pp. 1067–9.

11. A. J. McConnell, "A New Generator Differential Relay," *A.I.E.E. Trans.*, vol. 62, pp. 11–3, January, 1943. Disc., pp. 381–3, 1943.

12. T. A. Cramer, "Carrier-Current Differential Protection for Transformer Banks," *A.I.E.E. Trans.*, vol. 62, pp. 545–8, August, 1943. Disc., pp. 947–8.

13. "Grounding Switch Protects Transformer Installed near Center of 50-Mile Line," *Elec. Wld.*, vol. 121, no. 10, p. 58 (844), March 4, 1944.

14. V. M. Montsinger and G. Camilli, "Thermal Protection of Transformers under Overload Conditions," *A.I.E.E. Trans.*, vol. 63, pp. 160–4, April, 1944. Disc., pp. 444–6.

15. P. H. Adams, "Turbine-Generator Field Current Relay," *Elec. Wld.*, vol. 121, no. 26, pp. 58–9 (2342–3), June 24, 1944.

16. E. W. Tipton, "Relay for Air-Cooled Type Transformers," *Elec. Wld.*, vol. 122, no. 2, pp. 116, 118, July 8, 1944.

17. R. L. Webb and C. S. Murray, "Vibration Protection for Rotating Machinery," *A.I.E.E. Trans.*, vol. 63, pp. 534–7, July, 1944. Disc., pp. 1355–7.

18. A. H. Burkhalter, "Differential Protection of Generator Transformer Unit," *Elec. Wld.*, vol. 122, no. 6, pp. 87–9, Aug. 5, 1944.

19. E. W. Tipton, "An Automatic Watchman for Air-Cooled Transformers," *Westinghouse Engineer*, vol. 4, pp. 187–9, November, 1944.

20. L. F. Blume, G. Camilli, S. B. Farnham, and H. A. Peterson, "Transformer Magnetizing Inrush Currents and Influence on System Operation," *A.I.E.E. Trans.*, vol. 63, pp. 366–75, 1944. Disc., pp. 423–4.

21. G. Bertola, "Enhanced Transformer Protection through Inrush-Proof Ratio Differential Relays," *Brown Boveri Rev.* (Baden), vol. 32, pp. 129–33, April, 1945.

22. E. L. Michelson, "Rectifier Relay for Transformer Protection," *A.I.E.E. Trans.*, vol. 64, pp. 252–4, May, 1945.

23. E. G. Ratz, "Generator Protected by a 'Floating' C. T.," *Elec. Wld.*, vol. 124, no. 7, pp. 115–6, August 18, 1945.

24. Joseph M. De Guilmo, "Differential Protection, Delta-Wye Transformer Banks," *Elec. Wld.*, vol. 126, no. 5, p. 74, August 3, 1946; no. 7, p. 89, August 17; no. 9, pp. 74, 76, August 31; no. 11, pp. 114, 117, September 14, 1946.

25. J. R. Linders, "Differential Relay Protection Extended to Tertiary Wind-

ing," *Elec. Wld.*, vol. 126, no. 15, p. 100, October 12, 1946. Transformer differential protection which includes tertiary bus.

26. L. L. FOUNTAIN, "Motoring Protection for A-C Generators," *Westinghouse Engineer*, vol. 6, pp. 190–1, November, 1946.

27. A.I.E.E. RELAY SUBCOMMITTEE, "Protection of Powerhouse Auxiliaries," *A.I.E.E. Trans.*, vol. 65, pp. 746–51, November, 1946. Disc., pp. 1115–6.

28. ERIC T. B. GROSS, "Simplicity in Transformer Protection," *Elec. Eng.*, vol. 66, pp. 564–9, June, 1947. Gas-actuated relays.

29. A.I.E.E. RELAY SUBCOMMITTEE, "Relay Protection of Power Transformers," *A.I.E.E. Trans.*, vol. 66, pp. 911–5, 1947. Disc., pp. 915–7.

30. J. T. MADILL, "Typical Transformer Faults and Gas Detector Relay Protection," *A.I.E.E. Trans.*, vol. 66, pp. 1052–8, 1947. Disc., pp. 1058–60.

31. A. L. HOUGH, "Gas Detector Relays," *Canadian Elec. Assoc. Proc.* (Montreal), 57th annual convention, pp. 174–6, 1947.

I. Bus Protection

1. R. M. STANLEY and F. C. HORNIBROOK, "The Fault Ground Bus—Its Use and Design in Brunot Island Switch House of Duquesne Light Co.," *A.I.E.E. Trans.*, vol. 49, pp. 201–11, January, 1930. Disc., pp. 211–2.

2. W. A. LEWIS and R. M. SMITH, "Relay Protection for Station Buses," *Elec. Jour.*, vol. 34, pp. 451–8, November, 1937.

3. L. F. KENNEDY and C. D. HAYWARD, "Harmonic-Current-Restrained Relays for Differential Protection," *A.I.E.E. Trans.*, vol. 57, pp. 262–6, May, 1938. Disc., pp. 266–71.

4. A.I.E.E.-E.E.I. Committee Report, "Bus Protection," *A.I.E.E. Trans.*, vol. 58, pp. 206–11, May, 1939. Disc., pp. 211–2.

5. R. M. SMITH, W. K. SONNEMANN, and G. B. DODDS, "Considerations in Applying Ratio Differential Relays for Bus Protection," *A.I.E.E. Trans.*, vol. 58, pp. 243–9, June, 1939. Disc., pp. 249–52.

6. C. R. MASON, "Relay Protection of A-C Rotating Machines, Transformers, Buses, and Lines. Part II: Transformers and A-C Buses," *Gen. Elec. Rev.*, vol. 42, pp. 488–96, November, 1939.

7. E. C. WENTZ and W. K. SONNEMANN, "Current Transformers and Relays for High-Speed Differential Protection, with Particular Reference to Offset Transient Currents," *A.I.E.E. Trans.*, vol. 59, pp. 481–8, August, 1940. Disc., pp. 1144–8.

8. "Grounding Current-Transformer Secondaries," *Relaying News* (General Electric Co., Schenectady, N. Y.), no. 20, p. 3, January, 1941.

9. G. STEEB, "Bus Protection Independent of Current-Transformer Characteristics," *A.I.E.E. Trans.*, vol. 60, pp. 859–62, September, 1941. Disc., pp. 1365–8.

10. L. F. KENNEDY and A. T. SINKS, "New Current Transformer for Bus Differential Protection," *A.I.E.E. Trans.*, vol. 60, pp. 1180–7, 1941. Disc., pp. 1363–5.

11. E. C. WENTZ and W. K. SONNEMANN, "Predicting Performance of Bus-Differential Systems," *Westinghouse Engineer*, vol. 2, pp. 28–31, February, 1942.

12. GORDON W. GERELL, "Fault Bus-Differential Scheme Protects Cahokia Bus," *Elec. Wld.*, vol. 117, no. 16, pp. 53–4 (1335–6), April 18, 1942.

13. E. L. HARDER, "Air-Core Couplers Simplify Differential Protection," *Westinghouse Engineer*, vol. 2, pp. 43–5, May, 1942.

14. E. L. HARDER, E. H. KLEMMER, W. K. SONNEMANN, and E. C. WENTZ,

"Linear Couplers for Bus Protection," *A.I.E.E. Trans.*, vol. 61, pp. 241–8, May. 1942. Disc., pp. 463–5.

15. W. K. Sonnemann, "A New Single-Phase-to-Ground Fault-Detecting Relay," *A.I.E.E. Trans.*, vol. 61, pp. 677–80, September, 1942. Disc., pp. 995–6.

16. H. T. Seeley, "The Effect of Current-Transformer Residual Magnetism on Balanced-Current or Differential Relays," *A.I.E.E. Trans.*, vol. 62, pp. 164–9, April, 1943. Disc., p. 384.

17. C. A. Molsberry, "Distance-Relay Protection for Sectionalized Bus," *Elec. Wld.*, vol. 124, no. 7, pp. 96–8, Aug. 18, 1945.

18. G. W. B. Mitchell, "Busbar Zone Protection," *C.I.G.R.E.*, 1946, vol. 3, report 340, 12 pp.

19. H. T. Seeley and Frank von Roeschlaub, "Instantaneous Bus-Differential Protection Using Bushing Current Transformers," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1709–18, 1948. Disc., pp. 1718–9.

J. Instrument Transformers and Capacitor Potential Devices

1. D. E. Marshall and P. O. Langguth, "Current Transformer Excitation under Transient Conditions," *A.I.E.E. Trans.*, vol. 48, pp. 1464–74, October, 1929.

2. P. O. Langguth and R. M. Smith, "What the Tests Show," *Elec. Jour.*, vol. 30, pp. 98–101, March, 1933. Indianapolis tests on breakers, relays, and potential devices.

3. P. O. Langguth, "Capacitor Potential Devices," *Elec. Jour.*, vol. 31, pp. 107–9, 112, March, 1934.

4. E. L. Harder, P. O. Langguth, and C. A. Woods, Jr., "Transient and Steady-State Performance of Potential Devices," *A.I.E.E. Trans.*, vol. 59, pp. 91–9, February, 1940. Disc., pp. 99–102.

5. E. C. Wentz and W. K. Sonnemann, "Current Transformers and Relays for High-Speed Differential Protection, with Particular Reference to Offset Transient Currents," *A.I.E.E. Trans.*, vol. 59, pp. 481–8, August, 1940. Disc., pp. 1144–8.

6. J. P. Gebelein and J. A. Elzi, "Analysis of Bushing-Current-Transformer Performance," *A.I.E.E. Trans.*, vol. 59, pp. 541–6, September, 1940. Disc., pp. 1137–8.

7. G. Camilli and R. L. Ten Broeck, "A Proposed Method for the Determination of Current-Transformer Errors," *A.I.E.E. Trans.*, vol. 59, pp. 547–50, September, 1940. Disc., pp. 1138–40.

8. C. A. Woods, Jr., and S. A. Bottonari, "Overcurrent Performance of Bushing-Type Current Transformers," *A.I.E.E. Trans.*, vol. 59, pp. 554–60, September, 1940. Disc., pp. 1140–4.

9. A. T. Sinks, "Computation of Accuracy of Current Transformers," *A.I.E.E. Trans.*, vol. 59, pp. 663–8, December, 1940. Disc., pp. 1252–3.

10. J. E. Clem and P. O. Langguth, "Rating of Potential Devices and Suggested Material for a Standard," *A.I.E.E. Trans.*, vol. 59, pp. 676–80, December, 1940. Disc., pp. 1217–8.

11. G. Camilli, "New Developments in Current-Transformer Design," *A.I.E.E. Trans.*, vol. 59, pp. 835–42, 1940. Disc., pp. 1099–102.

12. E. C. Wentz, "A Simple Method for Determination of Ratio Error and Phase Angle in Current Transformers," *A.I.E.E. Trans.*, vol. 60, pp. 949–54, October, 1941. Disc., pp. 1369–70.

13. L. F. Kennedy and A. T. Sinks, "New Current Transformer for Bus

Differential Protection," *A.I.E.E. Trans.*, vol. 60, pp. 1180–7, 1941. Disc., pp. 1363–5.

14. A. C. Schwager, "Current Transformer Performance Based on Admittance-Vector Locus," *A.I.E.E. Trans.*, vol. 61, pp. 26–30, January, 1942. Disc., pp. 465–9.

15. E. L. Harder, E. H. Klemmer, W. K. Sonnemann, and E. C. Wentz, "Linear Couplers for Bus Protection," *A.I.E.E. Trans.*, vol. 61, pp. 241–8, May, 1942. Disc., pp. 463–5.

16. C. Concordia, C. N. Weygandt, and H. S. Shott, "Transient Characteristics of Current Transformers during Faults," *A.I.E.E. Trans.*, vol. 61, pp. 280–5, May, 1942. Disc., pp. 469–70.

17. A.I.E.E. Committee on Protective Devices, Current Transformer Subcommittee, "Current- and Potential-Transformer Standardization," *A.I.E.E. Trans.*, vol. 61, pp. 698–706, September, 1942. Disc., pp. 998–1000.

18. H. T. Seeley, "The Effect of Current-Transformer Residual Magnetism on Balanced-Current or Differential Relays," *A.I.E.E. Trans.*, vol. 62, pp. 164–9, April, 1943. Disc., p. 384.

19. S. D. Moreton, "A Simple Method for the Determination of Bushing-Current-Transformer Characteristics," *A.I.E.E. Trans.*, vol. 62, pp. 581–5, September, 1943. Disc., pp. 948–52.

20. A. Hobson, "Instrument Transformers," *I.E.E. Jour.*, vol. 91, part 2, pp. 147–63, April, 1944. Disc., pp. 163–8.

21. F. A. Olmsted, "How to Select Tap on Bushing C.T.," *Elec. Wld.*, vol. 121, no. 20. p. 112 (1792), May 13, 1944.

22. F. E. Davis, "Now Instrument Transformer Standards Make Sense!" *Allis-Chalmers Elec. Rev.*, vol. 9, no. 2, pp. 5–11, June, 1944.

23. Lloyd F. Hunt and J. H. Vivian, "One Ampere Current Transformer Proposed," *Elec. Wld.*, vol. 121, no. 26, pp. 59–60 (2343–4), June 24, 1944.

24. R. Koller, "Current-Transformer Output and Application Charts," *A.I.E.E. Trans.*, vol. 63, pp. 573–7, August, 1944. Disc., pp. 1422–3.

25. E. C. Wentz, "The Evolution of Standard Lines of Current Transformers for High Overcurrent Capacity," *A.I.E.E. Trans.*, vol. 63, pp. 658–62, September, 1944. Disc., pp. 1426–7.

26. H. B. Ashenden, "'When' and 'Why' Tips on Bushing Current Transformers," *Allis-Chalmers Elec. Rev.*, vol. 9, no. 3, pp. 24–9, September, 1944.

27. E. C. Goodale and J. I. Holbeck, "Field Determination of Current-Transformer Errors by the Secondary-Voltage Method," *A.I.E.E. Trans.*, vol. 63, pp. 879–82, December, 1944. Disc., pp. 1467–8.

28. E. L. Harder, E. H. Klemmer, and R. E. Neidig, "Linear Couplers: Field Tests and Experience at York and Middletown, Pa.," *A.I.E.E. Trans.*, vol. 65, pp. 107–13, March, 1946.

29. A.I.E.E. Relay Subcommittee, "Low-Current-Secondary Current Transformers," *A.I.E.E. Trans.*, vol. 65, pp. 649–50, October, 1946.

30. J. G. Wellings, "Current Transformers for Protective Gear," *C.I.G.R.E.*, 1946, vol. 3, report 342, 11 pp.

31. F. S. Rothe and C. Concordia, "Transient Characteristics of Current Transformers during Faults—II," *A.I.E.E. Trans.*, vol. 66, pp. 731–4, 1947.

K. Relay Testing and Fault Location

1. H. P. Dupuis and W. E. Jacobs, "Fault Location and Relay Performance

Analysis by Automatic Oscillographs," *A.I.E.E. Trans.*, vol. 65, pp. 442–6, July, 1946. Disc., pp. 1125–6.

2. W. A. Morgan and Byron Evans, "Relaying Difficulties Disclosed by Staged-Fault Tests," *A.I.E.E. Trans.*, vol. 67, part I, pp. 73–82, 1948.

L. Electronic Relays

1. Rolf Wideröe, "Thyratron Tubes in Relay Practice," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 1347–53, October, 1934.

2. R. H. Macpherson, A. R. van C. Warrington, and A. J. McConnell, "Electronic Protective Relays," *A.I.E.E. Trans.*, vol. 67, part II, pp. 1702–7, 1948. Disc., pp. 1707–8. Also in *Elec. Eng.*, vol. 68, pp. 122–8, February, 1949.

PROBLEMS ON CHAPTER IX

1. Derive an equation for the torque of a polyphase directional relay having the 30° connection (similar to eq. 3, p. 85, for the 90° connection).

2. Would false operation of distance relays occur in the event of a blown potential-transformer fuse? If so, how could it be prevented?

3. Prove, by the use of symmetrical components, that the balance point of a distance relay for a three-phase fault is approximately 15% farther from the relay than the balance point for a line-to-line fault if the relay operates on line current and adjacent line-to-line voltage. Assume the faults to have no impedance and to occur on a single line having no mutual impedance with any other line.

4. A 50-mile 110-kv. transmission line has a positive-sequence impedance of $0.25 + j0.82$ ohms per mile and a zero-sequence impedance of $0.64 + j2.14$ ohms per mile. The external system at each end of the line may be represented by a positive-sequence impedance of $0 + j30$ ohms in series with the nominal voltage of the system, a like value of negative-sequence impedance, and a zero-sequence impedance of $0 + j20$ ohms. Assume a fault at a point distant from the relays at one end by 90% of the line length, this fault to consist of arcs from two wires to ground. The resistance of each arc may be computed from the empirical equations given in the footnote on p. 91. How much does the scalar impedance presented to a 1-cycle impedance relay during this arcing fault differ from that during a metallic short circuit if the breaker at the distant end of the line is (*a*) closed and (*b*) open? What distance would the balance point of the relay shift in each case on account of arc resistance?

5. A 25-mile section of line lies beyond the 50-mile section described in Prob. 4. The second-zone impedance element of the relays, which has a 0.5-sec. delay, is set to reach 15 miles into this 25-mile section for a metallic fault. How much would the impedance presented to the relay increase because of arc resistance during an arcing two-line-to-ground fault at the normal balance point? Assume that the arcs are lengthened by a 25-m.p.h. wind.

6. In Prob. 4 a reactance relay is substituted for the impedance relay. How much does the apparent reactance change because of a ±60° phase difference between the e.m.f.'s of the two terminal systems?

7. Plot, in the complex power plane, the tripping characteristic of a current-voltage-product relay having maximum torque at 60° lag.

8. Plot, in the complex admittance plane, the tripping characteristics of the step-type impedance and reactance relays whose characteristics in the impedance plane are shown in Fig. 20, p. 95.

9. Expressions for the operating and restraining torques of the directional starting unit of an old Type GCX distance relay are given in the footnote on p. 94. Find the relative diameters, and the directions of the diameters through the origin, of the characteristic circles of this relay element in the impedance plane, for the following three conditions: (*a*) three-phase short circuit; (*b*) line-to-line short circuit, assuming balanced line-to-line voltages at relay; (*c*) line-to-line short circuit, assuming complete collapse of line-to-line voltage of faulted phase at relay.

10. Prove that the vector difference of the currents in the corresponding faulted-phase conductors of two identical parallel lines, one of which has an internal fault, is a fraction of the fault current that is equal to the ratio of the distance of the fault from the far end of the line to the entire length of one line. In the proof, assume that the fault has resistance, that there is mutual impedance between the two parallel lines, that the zero-sequence impedance of the lines differs from the positive-sequence impedance, and that all the sequence impedances of the remainder of the three-phase network differ from one another.

11. A coupling-capacitor unit for carrier current consists of a 0.001-μf. capacitor grounded through a 100-mh. radio-frequency choke coil. What portion of the line-to-ground voltage appears across the choke coil (*a*) at the power frequency of 60 c.p.s. and (*b*) at a carrier frequency of 100 kc.p.s.?

CHAPTER X

THE INFLUENCE OF SWINGING AND OUT-OF-STEP OPERATION UPON PROTECTIVE RELAYS

The principal relation of protective relays to the problem of power-system stability is their vital role of clearing faults as rapidly as possible in order to maintain stability. That aspect of relaying was considered in Chapter IX. Another important relation of relays to the stability problem is their action in opening unfaulted, or sound, lines when two or more synchronous machines or groups of machines swing with respect to one another or lose synchronism with one another. This aspect of relaying will now be considered.

The opening of a sound line during swings from which the system can recover is nearly always undesirable. Two reasons for this may be given. First, if the line has tapped load and is opened at both ends, service to that load is needlessly interrupted. Second, and much more important, however, is the fact that the tie between the swinging groups of machines—a tie already weakened by disconnection of the faulted line—is further weakened by the opening of a sound line. The tie could thus be weakened to such an extent that the system would become unstable even though it would have been stable if the false tripping had not occurred.

The opening of a sound line during out-of-step conditions is desired in some cases and not in others. When two groups of machines go out of step with each other, the continuing fluctuation of voltage severely disrupts service, and it is usually advisable to end the disturbance by separating the two groups of machines. However, it is desirable to select beforehand the point of separation so that there will be the least disruption of service. For example, the point might be chosen so that neither part of the system would have a deficiency of generating capacity for supplying its own load, or so as to avoid overloading of certain lines. In order to ensure that a system out of step will be split only at the proper point or points, it may be necessary to modify the relay system in one or both of the following ways: (1) If some of the protective relays which are provided for clearing faults trip their breakers during out-of-step conditions at places where such tripping is not desired, these relays must be changed so as to prevent the undesired tripping. (2) If other of the protective relays fail to trip during out-of-step conditions at places where such tripping is desired, these relays must be modified, or others added, to secure the desired tripping.

A single machine running out of step with other machines on the same bus (perhaps because of loss of excitation) not only may impair service but also may suffer damage itself, and it should be disconnected as soon as possible—preferably just before it falls out of step. Special relays have been devised for this purpose.

It is now apparent that relays may be required to distinguish among normal conditions, short circuits, swings of large amplitude, and out-of-step operation, and they may be called upon to take the desired action in each of these circumstances.

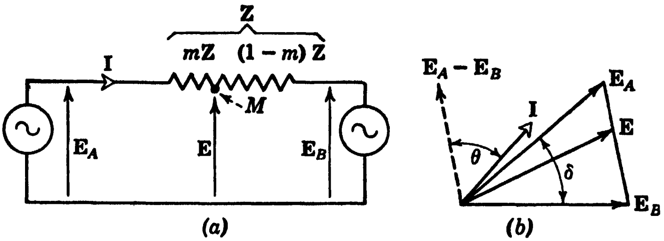


FIG. 1. Two-machine system used to show the effect of swings and out-of-step conditions on relay operation. (*a*) Circuit diagram. (*b*) Vector diagram.

Analysis of the effect of swinging and out-of-step conditions upon relays. When two machines or groups of machines are running out of synchronism, there is a moment in each slip cycle at which the phase difference of their internal voltages is 180°. At this moment, the electrical conditions are very much the same as if there were a three-phase short circuit approximately midway between the machines. That is, the line-to-line voltages at the apparent point of fault become zero, and the line currents are high. As a result, the relays can "see" a fault although there is none, and those relays protecting lines on which the fault appears to be will trip their circuit breakers.

When the two machines or groups of machines are swinging with respect to one another after the clearing of a severe fault, even though they do not lose synchronism with one another, there may be moments when the angular displacement between their internal voltages is so great that electrical conditions in the network approach those of a three-phase short circuit closely enough to deceive the relays.

The effects of swings and out-of-step operation on relays may well be studied by consideration of a simple two-machine system (Fig. 1). Here $\mathbf{E}_A$ and $\mathbf{E}_B$ are the voltages behind transient reactance, which are assumed constant in magnitude but varying in phase during swings or out-of-step conditions; $\mathbf{E}_A$ leads $\mathbf{E}_B$ by the variable angle δ. The current anywhere in the series circuit (with respect to $\mathbf{E}_B$ as reference) is

$$\mathbf{I} = \frac{E_A\angle\delta - E_B}{\mathbf{Z}} \tag{1}$$

where $\mathbf{Z}$ is the impedance of the connecting circuit, including the transient reactances of the two machines. Upon the assumption that the impedance of all parts of the circuit has the same angle, the total impedance $\mathbf{Z}$ is divided by the relay location M into two parts, $m\mathbf{Z}$ and $(1 - m)\mathbf{Z}$, where m is a real number less than 1. At point M the voltage $\mathbf{E}$ (with respect to $\mathbf{E}_B$ as reference) is then

$$\mathbf{E} = (1 - m)E_A\angle\delta + mE_B \tag{2}$$

Effect on distance relays. The impedance "seen" by the relays at M is

$$\mathbf{Z}_r = \frac{\mathbf{E}}{\mathbf{I}} = \frac{(1 - m)E_A\angle\delta + mE_B}{E_A\angle\delta - E_B}\mathbf{Z} \tag{3}$$

If E_A, E_B, and m are constant and δ is varied, the locus of $\mathbf{Z}_r$ in the complex impedance plane is either a circle or a straight line. Suppose, for simplicity, that $E_A = E_B$; then the locus is a straight line, as will be shown. Division of eq. 3 by $\mathbf{Z}$ and division of numerator and denominator by $E_A = E_B$ yield:

$$\begin{aligned}
\frac{\mathbf{Z}_r}{\mathbf{Z}} &= \frac{(1 - m)\angle\delta + m}{\angle\delta - 1} = \frac{-m(\angle\delta - 1) + \angle\delta}{\angle\delta - 1} \\
&= -m + \frac{1}{1 - \angle-\delta} = -m + \frac{1 + \angle\delta}{(1 - \angle-\delta)(1 + \angle\delta)} \\
&= -m + \frac{1 + \angle\delta}{1 + \angle\delta - \angle-\delta - 1} \\
&= -m + \frac{1 + \angle\delta}{\angle\delta - \angle-\delta} = -m + \frac{1 + \cos\delta + j\sin\delta}{2j\sin\delta} \\
&= \left(\frac{1}{2} - m\right) - j\left(\frac{1 + \cos\delta}{2\sin\delta}\right) \\
&= \left(\frac{1}{2} - m\right) - j\frac{1}{2}\cot\frac{\delta}{2}
\end{aligned} \tag{4}$$

This equation represents a vertical line, because the real part is constant while the imaginary part varies as a function of δ. Multiplication of each side of the equation by $\mathbf{Z}$ gives the locus of $\mathbf{Z}_r$; lengths are multiplied by the magnitude Z and the line is rotated counterclockwise through the impedance angle θ. The resulting loci are plotted in Fig. 2 for several values of m.*

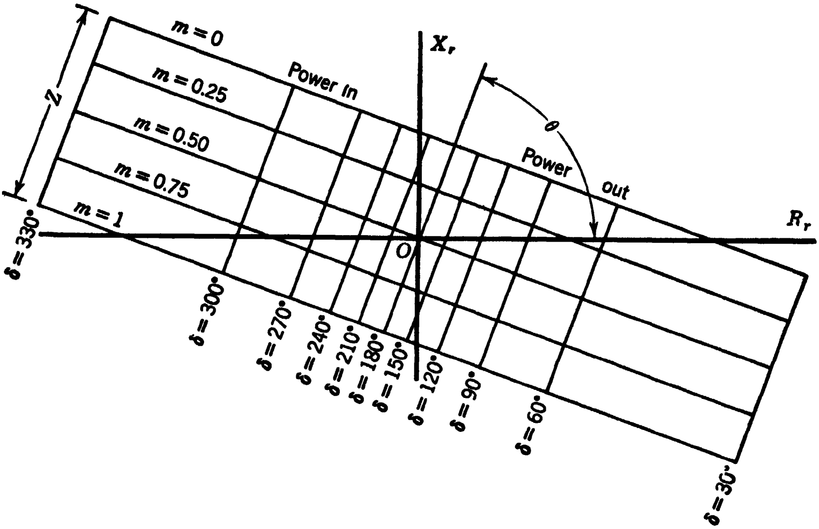


FIG. 2. Loci of impedance $R_r + jX_r$ "seen" by distance relays during swinging or out-of-step conditions on the two-machine system of Fig. 1 with $E_A = E_B$.

If the two generators are in phase with each other, the current is zero, and therefore the apparent impedance is infinite; but if the generators are 180° apart, the voltage becomes zero at the middle of the line, and therefore there appears to be a three-phase short circuit at that point ($m = \frac{1}{2}$).

If $E_A \neq E_B$, the loci are circular instead of straight. Then the impedance never becomes infinite. A proof of the shape of the loci is given later in this chapter, and some loci are calculated in Example 1 below.

The tripping characteristics of a distance relay (as illustrated in Figs. 20 and 21 of Chapter IX) may be plotted to the same scale on the same diagram with the impedance locus just discussed. It is then easy to determine what amplitude of swing will cause false tripping, either instantaneously or with delay. A diagram of this kind, drawn for the power system of Fig. 3, is shown in Fig. 4. The locus of impedance presented to the relay during short circuits is also drawn there. This impedance is directly proportional to the distance of the fault from the relay. In the region of principal interest in Fig. 4, the swing-impedance loci for all values of E_A/E_B which would be used in practice are so close to the straight line which is the locus for $E_A/E_B = 1$ that for most purposes it is accurate enough to use the straight line.

---

*Such loci were first presented by J. H. Neher in his discussion of Ref. 6.

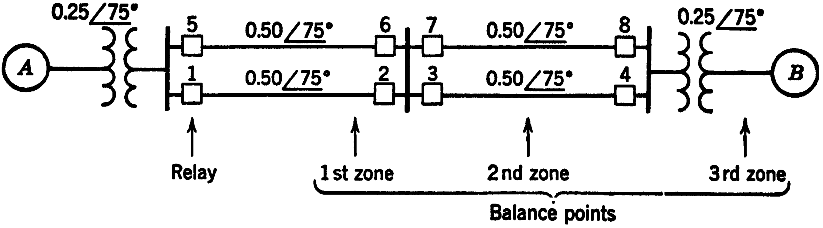


FIG. 3. Two-machine system used in Example 1 for analysis of relay operation during out-of-step conditions.

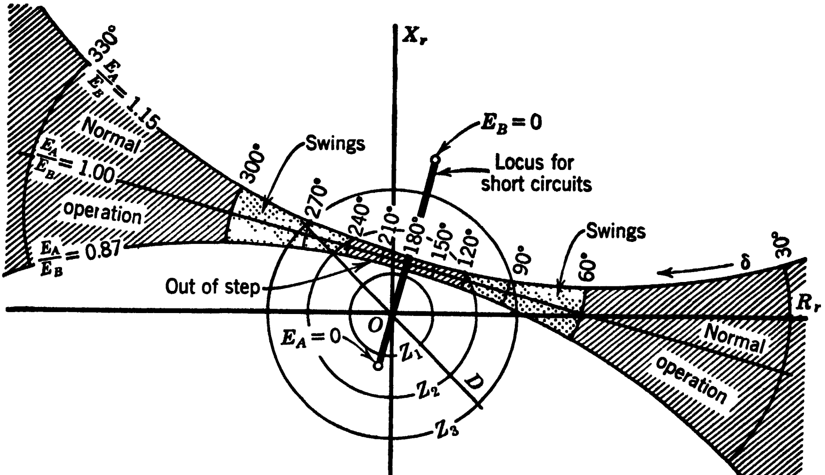


FIG. 4. Impedance "seen" by relay 1 in Fig. 3 during normal load conditions, swings, out-of-step conditions, and short circuits. The tripping characteristics of an impedance relay are also plotted.

The swing-impedance loci, the relay tripping characteristics, and the fault-impedance locus can be plotted in the admittance plane, if desired, instead of in the impedance plane. The admittance plot is less convenient because it has a nonuniform distance scale on the fault locus.

EXAMPLE 1

Calculate and plot the loci of impedance $\mathbf{Z}_r$ "seen" by the relays at circuit breaker 1 in Fig. 3 for $E_A/E_B = 1.15$, 1.00, and 0.87 and a variable angle δ between E_A and E_B. Also plot the tripping characteristics of a three-step impedance relay at breaker 1.

Solution. From Fig. 3, $\mathbf{Z} = 1.00\underline{/75^\circ}$ and, at breaker 1, $m = 0.25$.

(*a*) For $E_A/E_B = 1$, the locus of $\mathbf{Z}_r/\mathbf{Z}$ is given by eq. 4. This is a vertical line at a distance $\frac{1}{2} - m = 0.25$ to the right of the origin. The ordinates of points on this line representing various values of δ are given by the imaginary part of eq. 4:

$$y = -\frac{1}{2}\cot\frac{\delta}{2} \tag{a}$$

and are calculated in Table 1 for 30° increments in δ from 0° to 180°. From 180° to 360°, the values of y may be found from the relation

$$y(360^\circ - \delta) = -y(\delta) \tag{b}$$

TABLE 1

CALCULATION OF POINTS ON SWING-IMPEDANCE LOCUS FOR $E_A/E_B = 1.00$

(EXAMPLE 1)

δ	$\frac{\delta}{2}$	$\cot\frac{\delta}{2}$	y
0	0	∞	∞
30°	15°	3.732	−1.866
60°	30°	1.732	−0.866
90°	45°	1.000	−0.500
120°	60°	0.577	−0.289
150°	75°	0.268	−0.134
180°	90°	0	0

(*b*) For $E_A/E_B = 1.15$, eq. 3 gives

$$\frac{\mathbf{Z}_r}{\mathbf{Z}} = \frac{0.75 \times 1.15\underline{/\delta} + 0.25}{1.15\underline{/\delta} - 1.00} = \frac{0.86\underline{/\delta} + 0.25}{1.15\underline{/\delta} - 1.00} \tag{c}$$

The maximum value of this expression occurs at $\delta = 0$ and is

$$\frac{0.86 + 0.25}{1.15 - 1.00} = \frac{1.11}{0.15} = 7.40\underline{/0} \tag{d}$$

The minimum value occurs at $\delta = 180°$ and is

$$\frac{0.86 - 0.25}{1.15 + 1.00} = \frac{0.61}{2.15} = 0.28\underline{/0} \qquad (e)$$

As the locus is a circle, the center must lie midway between the maximum and minimum values, or at $(7.40 + 0.28)/2 = 3.84\underline{/0}$; and the radius must be half the difference of the maximum and minimum values, or $(7.40 - 0.28)/2 = 3.56$. Points on the locus for other values of δ are computed from eq. *c* in Table 2. The imaginary parts of $\mathbf{Z}_r/\mathbf{Z}$ do not differ greatly from those computed for $E_A/E_B = 1.00$. For δ between 180° and 360°, the values of $\mathbf{Z}_r/\mathbf{Z}$ are conjugates of those between 0 and 180° in reverse order.

(*c*) For $E_A/E_B = 0.87 = 1/1.15$, eq. 3 gives

$$\frac{\mathbf{Z}_r}{\mathbf{Z}} = \frac{0.75 \times 0.87\underline{/\delta} + 0.25}{0.87\underline{/\delta} - 1.00} = \frac{0.65\underline{/\delta} + 0.25}{0.87\underline{/\delta} - 1.00} \qquad (f)$$

Upon multiplication of numerator and denominator by $1.15\underline{/-\delta}$, this becomes

$$\frac{\mathbf{Z}_r}{\mathbf{Z}} = \frac{0.75 + 0.29\underline{/-\delta}}{1.00 - 1.15\underline{/-\delta}} \qquad (g)$$

Subtraction of 0.50 gives

$$\frac{(0.75 + 0.29\underline{/-\delta}) - (0.50 - 0.58\underline{/-\delta})}{1.00 - 1.15\underline{/-\delta}} = \frac{0.25 + 0.87\underline{/-\delta}}{1.00 - 1.15\underline{/-\delta}} \qquad (h)$$

which is the negative conjugate of eq. *c*. Therefore, the locus of $\mathbf{Z}_r/\mathbf{Z}$ for $E_A/E_B = 0.87$ is the image of that for $E_A/E_B = 1.15$ with respect to the vertical line which is the locus for $E_A/E_B = 1.00$.

The values of $\mathbf{Z}_r/\mathbf{Z}$ on the three loci derived above are multiplied by $\mathbf{Z} = 1.00\underline{/75°}$ to get $\mathbf{Z}_r$. This rotates the loci counterclockwise 75°. In addition, the values of impedance should be multiplied by 2, because the derivation of the loci used the entire current between *A* and *B*, although only half that current flows in the protected line. The resulting loci are plotted in Fig. 4.

(*d*) Let the first-zone impedance element of the relays at breaker 1 reach to 80% of the length of the line which it protects, or to $0.80 \times 0.50Z = 0.40Z$. Let the second-zone element be set at $0.80Z$, and the third-zone element at $1.20Z$. The tripping characteristics of these elements are concentric circles of radii $0.40Z$, $0.80Z$, and $1.20Z$, respectively, with centers at the origin. Let the directional element have maximum torque at a phase angle of 45°. Its characteristic is a straight line through the origin and perpendicular to the line of maximum torque. These characteristics are plotted in Fig. 4.

The diagram shows that instantaneous tripping of this particular relay will not occur during swinging or out-of-step operation, but that delayed

TABLE 2

CALCULATION OF POINTS ON THE SWING-IMPEDANCE LOCUS FOR $E_A/E_B = 1.15$ FROM EQ. *c*, EXAMPLE 1

δ	$0.86\underline{/\delta}$	$0.86\underline{/\delta} + 0.25$	$1.15\underline{/\delta}$	$1.15\underline{/\delta} - 1.00$	Z_r/Z
30°	$0.86\underline{/30^\circ} = 0.75 + j0.43$	$1.00 + j0.43 = 1.09\underline{/23.3^\circ}$	$1.15\underline{/30^\circ} = 1.00 + j0.58$	$0 + j0.58 = 0.58\underline{/90^\circ}$	$1.88\underline{/-66.7^\circ} = 0.74 - j1.72$
60°	$0.86\underline{/60^\circ} = 0.43 + j0.75$	$0.68 + j0.75 = 1.01\underline{/47.8^\circ}$	$1.15\underline{/60^\circ} = 0.58 + j1.00$	$-0.42 + j1.00 = 1.08\underline{/112.9^\circ}$	$0.94\underline{/-65.1^\circ} = 0.39 - j0.85$
90°	$0.86\underline{/90^\circ} = 0.00 + j0.86$	$0.25 + j0.86 = 0.90\underline{/73.8^\circ}$	$1.15\underline{/90^\circ} = 0 + j1.15$	$-1.00 + j1.15 = 1.53\underline{/131.0^\circ}$	$0.59\underline{/-57.2^\circ} = 0.32 - j0.50$
120°	$0.86\underline{/120^\circ} = -0.43 + j0.75$	$-0.18 + j0.75 = 0.77\underline{/103.5^\circ}$	$1.15\underline{/120^\circ} = -0.58 + j1.00$	$-1.58 + j1.00 = 1.87\underline{/147.7^\circ}$	$0.41\underline{/-44.2^\circ} = 0.29 - j0.29$
150°	$0.86\underline{/150^\circ} = -0.75 + j0.43$	$-0.50 + j0.43 = 0.66\underline{/139.1^\circ}$	$1.15\underline{/150^\circ} = -1.00 + j0.58$	$-2.00 + j0.58 = 2.08\underline{/163.8^\circ}$	$0.32\underline{/-24.7^\circ} = 0.29 - j0.13$

tripping will occur if the angle δ between generators A and B lies between about 90° and 270° for a long enough time to close the timer contacts.

At $\delta = 180^\circ$ the voltage and current—and hence the impedance—are identical with those of a three-phase short circuit about half-way between A and B (the exact location varying slightly with the ratio E_A/E_B). This location lies in the second zone of the relay being considered, but it could lie in the first, or instantaneous, zone of some other relay, such as that at breaker 3, Fig. 3.

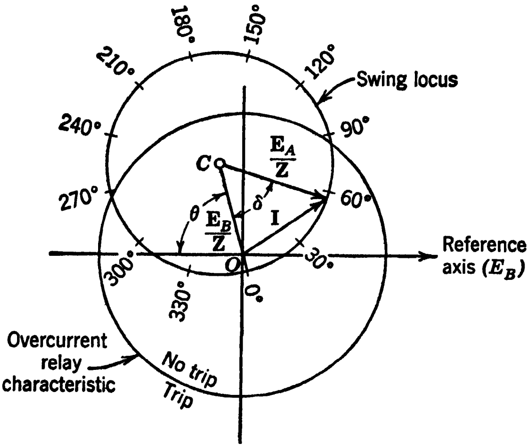


FIG. 5. Locus of vector current of the two-machine system of Fig. 1 during swinging or out-of-step conditions, and tripping characteristic of an overcurrent relay. The reference vector is $\mathbf{E}_B$. $E_A = 1.15$, $E_B = 1.00$, $Z\angle\theta = 1.00\angle 75^\circ$. The relay is set at $I = 1.50$.

Effect on overcurrent relays. The performance of overcurrent relays may be investigated by plotting the tripping characteristic and the current locus in the complex *current plane* instead of in the impedance plane. The current locus of the two-machine system of Fig. 1 is given by eq. 1 and is drawn in Fig. 5. It is a circle with center at the end of the vector $-\mathbf{E}_B/\mathbf{Z} = (E_B/Z)\angle 180^\circ - \theta$ and radius E_A/Z. Angle δ is the central angle of this circle and is measured counterclockwise from the end of the radius which points toward the origin. The tripping characteristic of the overcurrent relay, a circle centered at the origin, is also drawn in Fig. 5. The same information is presented in rectangular coordinates, I against δ, in Fig. 6. With the overcurrent relay set to trip at 1.5 units of current, tripping will occur if δ enters the range 90° to 270°.

In Fig. 5 the current vector is plotted with respect to $\mathbf{E}_B$ as the reference phase. If it is desired to show the tripping characteristic of a

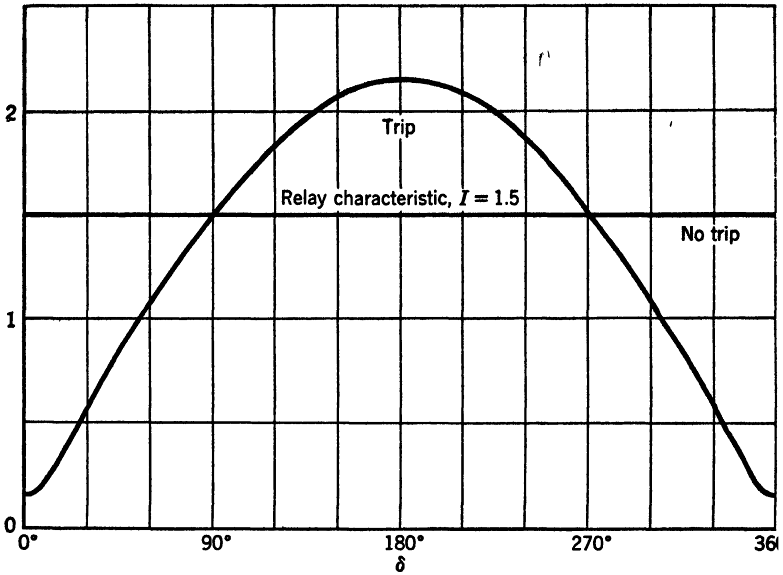


FIG. 6. Current magnitude I in the two-machine system of Fig. 1 as a function of angle δ during swinging or out-of-step conditions.

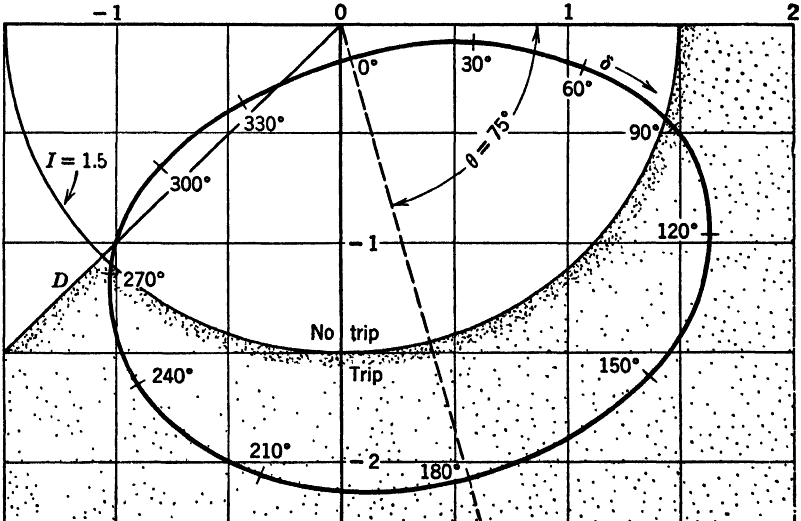


FIG. 7. Locus of vector current of the two-machine system of Fig. 1 during swinging or out-of-step conditions, and tripping characteristics of a directional overcurrent relay at $m = 0.25$. The reference vector is the voltage at $m = 0.25$. $E_A = 1.15$, $E_B = 1.00$, $Z = 1.00\underline{/75°}$.

directional overcurrent relay, it is preferable to use the voltage at the relay location as reference phase. A current locus of this kind, with the voltage at $m = 0.25$ as reference phase, is calculated in Example 2 below and is plotted in Fig. 7, together with the tripping characteristic of a directional overcurrent relay. Such loci are not circular except for $m = 1$ (Fig. 5) and $m = 0$.

EXAMPLE 2

Calculate and plot the locus of the current vector of the two-machine system of Fig. 1, using the voltage at $m = 0.25$ as reference phase. Take $E_A = 1.15$, $E_B = 1.00$, and $\mathbf{Z} = 1\underline{/75^\circ}$ per unit. Also plot the tripping characteristics of a directional overcurrent relay at $m = 0.25$, having a current element set to pick up at 1.5 per unit current and a directional element with maximum torque at 45° lag.

Solution. From eq. 1, the current (with respect to $\mathbf{E}_B$ as reference phase) is

$$\mathbf{I} = \frac{1.15\underline{/\delta} - 1.00}{1.00\underline{/75^\circ}} = (1.15\underline{/\delta} - 1.00)\underline{/-75^\circ} \qquad (a)$$

To express this current with respect to the voltage at $m = 0.25$, the phase of this voltage with respect to $\mathbf{E}_B$, which will be called α, must be subtracted from the phase of $\mathbf{I}$ as given above; thus

$$\mathbf{I}\underline{/-\alpha} = (1.15\underline{/\delta} - 1.00)\underline{/-75^\circ - \alpha} \qquad (b)$$

TABLE 3

COMPUTATION OF VECTOR CURRENT LOCUS FOR THE TWO-MACHINE SYSTEM OF FIG. 1, USING THE VOLTAGE AT $m = 0.25$ AS REFERENCE PHASE

(EXAMPLE 2)

δ	$\mathbf{I}\underline{/-\alpha}$ (per unit)
0°	$0.15\angle(0^\circ - 75^\circ - 0^\circ = -75^\circ) = 0.04 - j0.14$
30°	$0.58\angle(90^\circ - 75^\circ - 23^\circ = -8^\circ) = 0.57 - j0.08$
60°	$1.08\angle(113^\circ - 75^\circ - 48^\circ = -10^\circ) = 1.06 - j0.19$
90°	$1.53\angle(131^\circ - 75^\circ - 74^\circ = -18^\circ) = 1.45 - j0.47$
120°	$1.87\angle(148^\circ - 75^\circ - 104^\circ = -31^\circ) = 1.60 - j0.96$
150°	$2.08\angle(164^\circ - 75^\circ - 139^\circ = -50^\circ) = 1.34 - j1.60$
180°	$2.15\angle(180^\circ - 75^\circ - 180^\circ = -75^\circ) = 0.56 - j2.07$
210°	$2.08\angle(196^\circ - 75^\circ - 221^\circ = -100^\circ) = -0.36 - j2.05$
240°	$1.87\angle(212^\circ - 75^\circ - 256^\circ = -119^\circ) = -0.90 - j1.64$
270°	$1.53\angle(229^\circ - 75^\circ - 286^\circ = -132^\circ) = -1.02 - j1.14$
300°	$1.08\angle(247^\circ - 75^\circ - 312^\circ = -140^\circ) = -0.80 - j0.67$
330°	$0.58\angle(270^\circ - 75^\circ - 337^\circ = -142^\circ) = -0.46 - j0.36$

In Table 2, Example 1, values of $1.15\angle\delta - 1.00$ are given in column 5, and values of α are given in the angle signs in column 3. From these values, $I\angle{-\alpha}$ is computed in Table 3 and is plotted, together with the tripping characteristics, in Fig. 7.

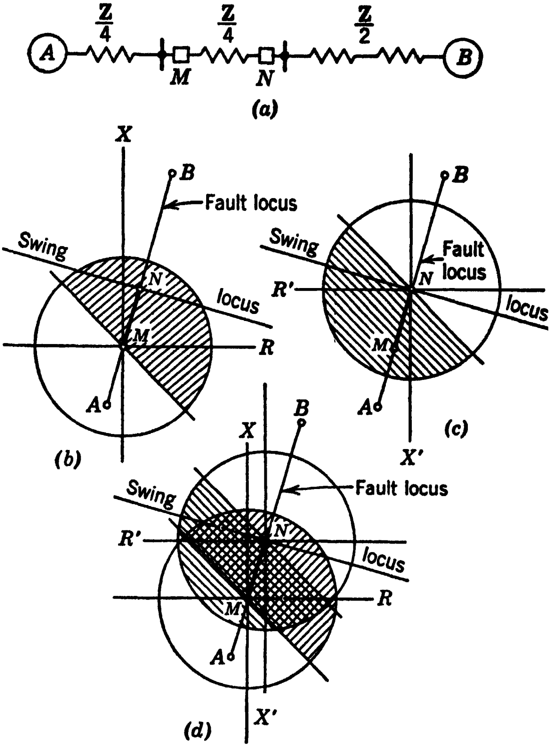


FIG. 8. Superposition of the tripping characteristics of impedance relays at opposite ends of a transmission line MN to give the tripping characteristic of a carrier-pilot relay system. (a) One-line diagram of transmission circuit. M and N are at $m = 0.25$ and 0.50, respectively. (b) Tripping characteristic of relays at M. (c) Tripping characteristic of relays at N. (d) Superposed characteristics. The tripping area is double-cross-hatched.

Effect on carrier-pilot relays. The tripping characteristics of distance-type carrier-pilot relays are similar to those of directional distance relays set to reach beyond the end of the protected line, except that tripping occurs only when tripping indications are given simultaneously at both ends of the line. The circumstances under which this may occur are conveniently found by superposing the characteristics of the relays at the two ends, as shown in Fig. 8.

In parts *b* and *c* of this figure are plotted the individual characteristics of the relays at the two ends of the line, *M* and *N*, respectively (see part *a* of the figure). Each characteristic, shown by a shaded area, results from the combination of an impedance element, reaching to 1.6 times the length of the protected section *MN*, and a directional element giving maximum torque at 45° lag. The shaded area for the relays at *N* is similar to that for the relays at *M*, except that it is turned 180°, because the relays at *M* act for faults to the right of *M*, but those at *N* act for faults to the left of *N*. The loci of impedance seen by the relays during faults and during swings are also plotted. Fault impedances lie on the line *AB*; faults in the protected section lie on segment *MN* of this line. The swing-impedance locus (for $E_A = E_B$) is a straight line perpendicular to line *AB* and intersecting that line at its midpoint *N*, where the voltage becomes zero when E_A and E_B are in phase opposition. Since both the fault locus and the swing locus for the relays at *M* are identical with those for the relays at *N*, except that the origin of coordinates is point *M* in one case and point *N* in the other, the two diagrams may be superposed, as in part *d* of the figure. Here coordinates *R* and *X* apply to impedances seen by the relays at *M*; coordinates R' and X', to impedances seen by the relays at *N*. The fault locus and the swing locus hold for both sets of relays, and any point on either locus represents, in the two sets of coordinates, the impedances seen simultaneously by the two sets of relays. The double-cross-hatched area is the carrier tripping area. A solid† fault anywhere on the protected section *MN* presents an impedance lying in this area, but an external fault presents an impedance outside this area. The swing locus crosses the tripping area, and tripping occurs for values of δ between 180° and about 240°.

Some carrier-pilot relays utilize distance relays which can trip independently of carrier under some circumstances. Such relays should be investigated as to both their carrier and noncarrier tripping characteristics. For example, in a carrier-pilot system using first-zone impedance elements which trip independently of carrier and second-zone impedance elements which trip under carrier supervision, the tripping characteristics are as shown in Fig. 9. The areas of instantaneous noncarrier tripping are shaded diagonally; that of carrier tripping is shaded vertically. In this scheme the instantaneous noncarrier trip areas lie entirely inside the carrier trip area and therefore present no additional hazard of tripping during swings. This may not be true of all schemes. In some of the unshaded areas of Fig. 9 there may be time-delay tripping independent of carrier, which would trip the lines on swings or on loss of synchronism if the operating point should remain inside the trip area long enough.

---

†A fault with resistance cannot be represented accurately by one point on the combined diagram, because the resistance should be added to the right of line *AB* for relays at *M*, but to the left for the relays at *N*. Thus, two points are needed, one for each set of relays. If each point lies in the trip-indication area of its own relay, tripping will occur.

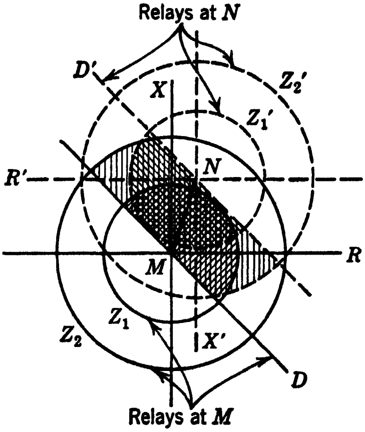


FIG. 9. Carrier and noncarrier tripping characteristics of carrier-pilot impedance relays. Diagonally shaded areas bounded by D and Z_1 and by D' and Z_1' represent noncarrier tripping at ends M and N, respectively. Vertically shaded area bounded by D, Z_2, D', and Z_2' represents carrier tripping.

Long lines. If the impedance of the protected transmission line is a large portion of the impedance **Z** between the internal voltages $\mathbf{E}_A$ and $\mathbf{E}_B$, there is a greater likelihood of tripping on swings than if the line impedance is a small portion of **Z**. This is true both for distance relays and for carrier-pilot schemes using distance relays. Figure 10 shows the tripping characteristics of impedance carrier-pilot relays on a line having an impedance $\mathbf{Z}/2$, with ends at $m = 0.25$ and $m = 0.75$. Comparison of this figure with Fig. 8*d*, for a line half as long (with impedance $\mathbf{Z}/4$ and with ends at $m = 0.25$ and $m = 0.50$) shows that the impedance-relay characteristic circles are larger for the long line than for the short one. This not only makes it more certain that the swing-impedance locus will pass through the tripping area but also increases the angular range of this locus which lies within the tripping area. Therefore smaller angular swings suffice to cause tripping on the long line than on the short one. Indeed, a heavily loaded long line may be tripped even under normal-load conditions or during very small swings.

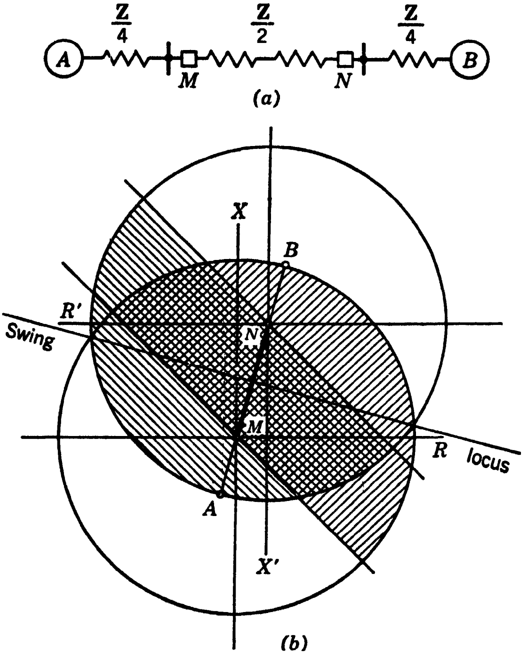


FIG. 10. Tripping characteristics of carrier-pilot relays on a long line. (a) One-line diagram of transmission circuit, showing location of relays M and N at $m = 0.25$ and 0.75, respectively. (b) Tripping characteristic, showing greater tripping area than that of short line (Fig. 8*d*).

Effect on other kinds of relays. *Ground relays* are not affected by swings or by out-of-step conditions, because these conditions do not produce zero-sequence current or voltage.

Balanced-current relays protecting parallel transmission lines are not affected by swings or by out-of-step conditions. The back-up relays used with them may be affected, however.

Pilot relays operating on the current-comparison or phase-comparison principle are not affected, but the back-up relays may be. Pilot relays operating on the *directional-comparison principle* are affected, as has been discussed under the heading "Carrier-pilot relays." Pilot relays operating on the *transferred-trip principle* are affected the same as nonpilot relays.

More complex systems. The operation of protective relays during swinging and out-of-step conditions on power systems more complex than the two-machine system of Fig. 1, which has been considered, may be analyzed readily by obtaining impedance or current loci by use of an a-c. calculating board. If a two-machine system is being considered, the phase of the power source representing one machine may be varied, while the phase of the other power source and the voltage magnitudes of both sources are held constant; and the required relay voltages and currents for various values of δ may be measured in complex form. If a multimachine system is being considered, swing curves may be obtained in the usual way; and, in the course of obtaining these curves, the required complex voltages and currents may be measured for various instants of time. An example of an impedance locus obtained in this way is shown in Fig. 11. Its general resemblance to the locus for a two-machine system may be noted.

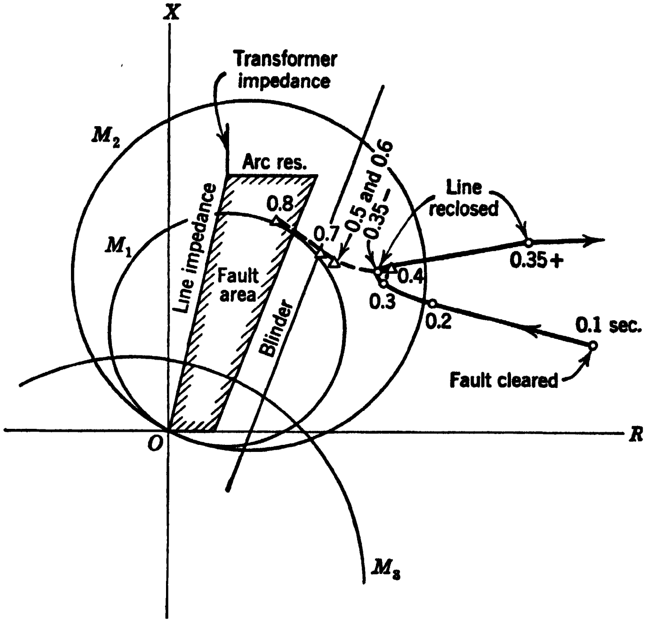


FIG. 11. Impedances seen by relay on line 1 during swing after clearing of two-line-to-ground fault on line 2. *Solid line:* system stable with reclosure. *Broken line:* system unstable without reclosure. Times are given in seconds after occurrence of fault. M_1, M_2, M_3, and "Blinder" are relay characteristics. (Adapted from Ref. 23 by permission)

The general swing-impedance locus of the two-machine system. The value of the swing-impedance locus in the analysis of the performance of distance relays has been shown in preceding sections of this chapter. In order to simplify the analysis, attention was limited to the system of Fig. 1, in which two machines are connected through series impedance. Furthermore, only the condition of equal internal generator voltages ($E_A = E_B$) was fully treated. In view of the importance of the swing-impedance locus, however, a fuller treatment is warranted. The analysis will, therefore, be extended to include consideration of (1) either equal or unequal generated voltages, (2) networks in which there are other paths between the two machines besides the path through the considered relays, (3) networks with shunt capacitance or shunt loads, and (4) the impedance seen by the relays on the unfaulted phases during unsymmetrical faults.

The impedance $\mathbf{Z}_r$ seen by any relay, connected in any manner, located anywhere on a two-machine power system, faulted or unfaulted, varies in the following manner[17] (to be proved in the next section):

1. If the internal voltages $\mathbf{E}_A$ and $\mathbf{E}_B$ are of constant magnitudes E_A and E_B but of varying phase difference δ, $\mathbf{Z}_r$ varies on a locus (the swing-impedance locus) which is either a straight line or a circle.
2. Each different ratio of magnitudes, E_A/E_B, gives a different locus, all but one of which are circles. Each circle surrounds one or the other of two points called *poles* (*A* and *B* in Fig. 12). The centers of these circles lie on the straight line through the poles. One ratio E_A/E_B gives a straight line (*GH*, Fig. 12) which is the perpendicular bisector of the line segment *AB* connecting the poles.
3. If the phase difference δ is constant and the magnitude ratio E_A/E_B varies, then the locus of $\mathbf{Z}_r$ is a circular arc or straight line extending from one pole to the other. The centers of these arcs lie on line *GH*. The principal use of these arcs is that their intersections with the swing-impedance loci serve to mark the values of δ on these loci.
4. The constant-angle arcs are orthogonal to the constant-magnitude circles. The two sets of loci, taken together, form an *impedance chart*, an example of which is given in Fig. 12.

The impedance chart for any particular case can be derived from the *general impedance chart* of Fig. 13 by altering the latter with respect to scale, orientation, and location and with respect to the labelling of the circles. The general chart is drawn with its poles on the real axis at $1 + j0$ and $-1 + j0$. The magnitude circles are labelled in terms of KE_A/E_B instead of E_A/E_B, and the angle arcs are labelled in terms of ϕ instead of δ.

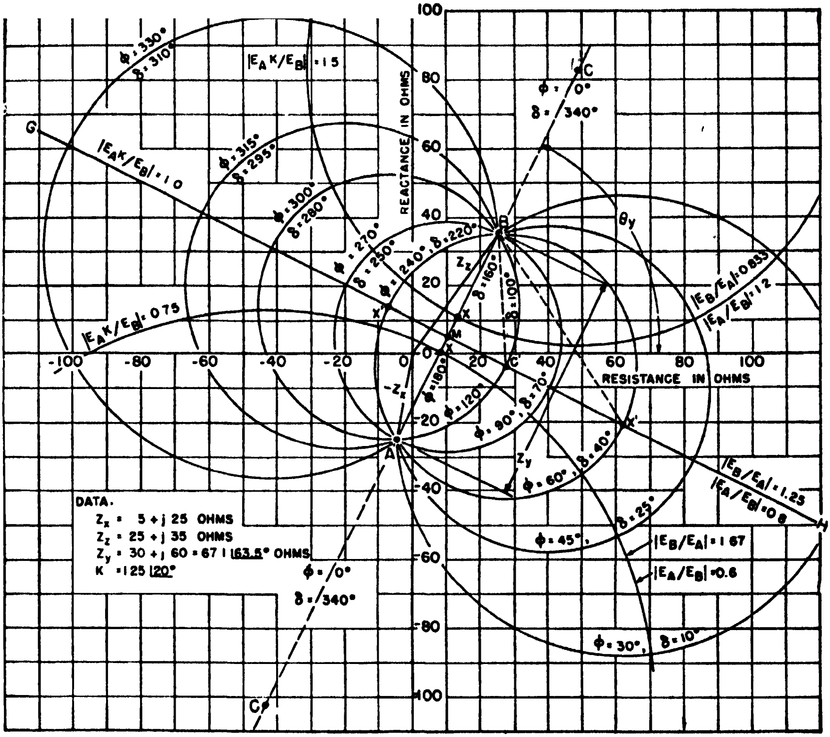


FIG. 12. Typical chart of the impedance seen by a relay in a two-machine power system as a function of the magnitude and angle of the vector ratio $\mathbf{E}_A/\mathbf{E}_B = (E_A/E_B)\underline{/\delta}$. In this particular chart, $\mathbf{Z}_A = -5 - j25$ ohms, $\mathbf{Z}_B = 25 + j35$ ohms, and $\mathbf{K} = 1.25\underline{/20°}$. (From Ref. 17 by permission)

The data required for altering the general impedance chart to fit a particular case are provided by measurement or calculation of the impedance seen by the relay under three different conditions, as follows:

$\mathbf{Z}_A$, the impedance seen when $\mathbf{E}_A = 0$;
$\mathbf{Z}_B$, the impedance seen when $\mathbf{E}_B = 0$; and
$\mathbf{Z}_K$, the impedance seen when $\mathbf{E}_A = \mathbf{E}_B$.

The poles, A and B, of the chart are located at points whose coordinates are $\mathbf{Z}_A$ and $\mathbf{Z}_B$, respectively, in the $\mathbf{Z}_r$ plane. Thus the values of these two impedances fix the scale, orientation, and location of the chart with respect to the R_r and X_r axes. The circles of the chart may be drawn either by tracing Fig. 13—in which case the scale must be that

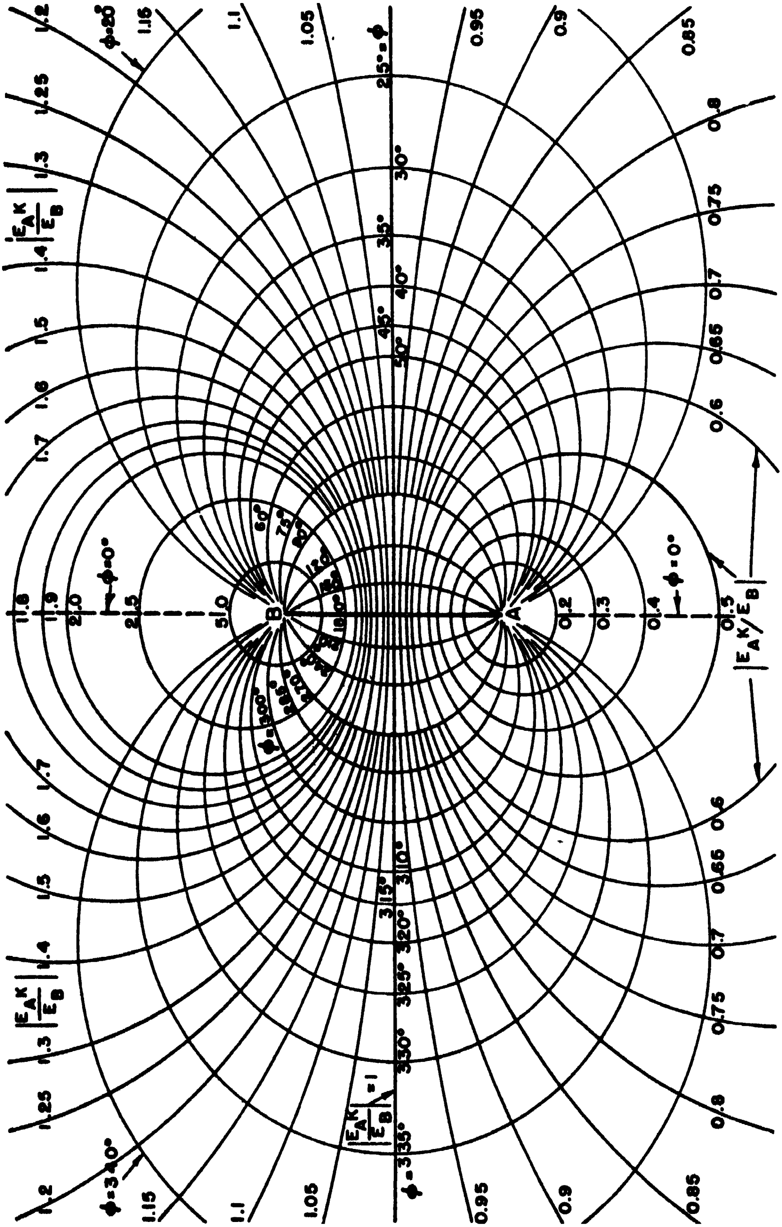


FIG. 13. General impedance chart. (From Ref. 17 by permission)

of Fig. 13—or by constructing a similar figure, to the desired scale, from the information of Tables 4 and 5.

TABLE 4

DATA FOR CONSTRUCTION OF IMPEDANCE CHART
RADII AND INTERSECTIONS WITH LINE AB OF CIRCLES FOR CONSTANT VALUES OF E_A/E_B IN TERMS OF LENGTH AB AND KE_A/E_B

(From Ref. 17 with permission)

KE_A/E_B	r/AB	MX/AB	KE_A/E_B	r/AB	MX/AB
0	0	−0.5000	1.25	2.222	0.0556
0.1	0.101	−0.4091	1.3	1.884	0.0652
0.2	0.208	−0.3333	1.35	1.641	0.0745
0.3	0.330	−0.2692	1.4	1.458	0.0833
0.4	0.476	−0.2143	1.45	1.315	0.0918
0.5	0.667	−0.1667	1.5	1.200	0.1000
0.55	0.789	−0.1452	1.55	1.105	0.1078
0.6	0.938	−0.1250	1.6	1.026	0.1154
0.65	1.126	−0.1061	1.65	0.958	0.1226
0.7	1.373	−0.0882	1.7	0.899	0.1296
0.75	1.714	−0.0714	1.75	0.848	0.1364
0.8	2.222	−0.0556	1.8	0.804	0.1429
0.85	3.063	−0.0405	1.85	0.764	0.1491
0.9	4.737	−0.0263	1.9	0.728	0.1552
0.95	9.744	−0.0128	1.95	0.696	0.1610
1.0	∞	0	2.0	0.667	0.1667
1.05	10.244	0.0122	2.5	0.476	0.2143
1.10	5.238	0.0238	5.0	0.208	0.3333
1.15	3.566	0.0349	10.0	0.101	0.4091
1.20	2.727	0.0455	∞	0	0.5000

r is the radius of the circle; X is its intersection with AB. See Fig. 12. MX is the distance from M, the midpoint of AB, to X in the positive direction MB. The center of the circle C is on AB (extended). MC has the sign of MX. $|MC| = r + |MX|$.

In order to change the labelling of the magnitude circles from KE_A/E_B to E_A/E_B, it is necessary to divide the values on the general chart by K. In order to change the labelling of the angle arcs from ϕ to δ, it is necessary to subtract θ_K. Both K and θ_K are given by

$$K\underline{/\theta_K} = \mathbf{K} = \frac{\mathbf{Z}_K - \mathbf{Z}_A}{\mathbf{Z}_K - \mathbf{Z}_B} \qquad [5]$$

The change of labelling completes the construction of the impedance

TABLE 5

DATA FOR CONSTRUCTION OF IMPEDANCE CHART
LOCATION OF CENTERS OF ARCS FOR CONSTANT VALUES OF δ IN TERMS OF LENGTH AB WITH ANGLE $\phi = \delta + \theta_K$

(From Ref. 17 with permission)

$\phi^\circ = \delta + \theta_K$	MC'/AB	$\phi^\circ = \delta + \theta_K$	MC'/AB	$\phi^\circ = \delta + \theta_K$	MC'/AB
0, 180	∞	60, 240	0.2887	120, 300	−0.2887
5, 185	5.715	65, 245	0.2332	125, 305	−0.3501
10, 190	2.836	70, 250	0.1820	130, 310	−0.4196
15, 195	1.866	75, 255	0.1340	135, 315	−0.5000
20, 200	1.374	80, 260	0.0882	140, 320	−0.596
25, 205	1.072	85, 265	0 0437	145, 325	−0.714
30, 210	0.866	90, 270	0	150, 330	−0.866
35, 215	0.714	95, 275	−0.0437	155, 335	−1.072
40, 220	0.596	100, 280	−0.0882	160, 340	−1.374
45, 225	0.500	105, 285	−0 1340	165, 345	−1.866
50, 230	0.4196	110, 290	−0.1820	170, 350	−2.836
55, 235	0.3501	115, 295	−0.2332	175, 355	−5.715

MC' is the distance from M, the midpoint of AB, to C', the center of the arc on GMH. See Fig. 12. MX' is the distance from M to X', the intersection of the arc with GMH in the positive direction MH. If ϕ is between 0° and 180°, MX' is positive; if ϕ is between 180° and 360°, MX' is negative.

chart for any particular relay and particular fault condition or normal condition.

The three impedances, $\mathbf{Z}_A$, $\mathbf{Z}_B$, and $\mathbf{Z}_K$, can be determined by any desired method of network solution, either with or without a calculating board. Inasmuch as these impedances are defined in such manner that the network has only one impressed voltage for each, they may be found through use of a d-c. calculating board, subject, of course, to the usual limitations of a d-c. board, namely, that shunt capacitance and shunt loads must be neglected, and that all branches of the network must be assumed to have the same impedance angle. These assumptions give $\mathbf{Z}_K = \infty$ and $\mathbf{K} = 1$ for an unfaulted network. A faulted network may be solved either by means of symmetrical components or by means of two-phase coordinates. The latter are recommended as simpler. Both methods are explained in Chapter VI, Vol. I.

EXAMPLE 3[17]

A simple two-machine power system is shown in Fig. 14. Distance relays, operating on delta voltage and delta current, are located at R. (a) Construct charts for portraying the variation of impedance seen by each of the relays when there is a line-to-line fault on phases b and c at point F. (*b*) Assuming $E_A/E_B = 1$, combine on one chart the impedance loci for the fault condition and the locus of impedance seen by the relays during power swings when there is no fault.

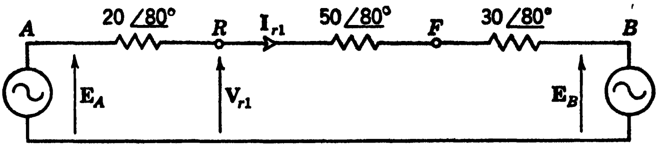


FIG. 14. Positive-sequence diagram of a simple two-machine power system (Example 3). Impedances are given in ohms. The swing-impedance loci of distance relays at R are plotted in Figs. 15, 16, and 17 for a line-to-line fault at F and for no fault.

Solution. The impedances seen by relays operating on delta voltage and current, expressed in terms of phase quantities, symmetrical components, and two-phase coordinates, are:

$$\mathbf{Z}_{cb} = \frac{\mathbf{V}_{rA}}{\mathbf{I}_{rA}} = \frac{\mathbf{V}_{rc} - \mathbf{V}_{rb}}{\mathbf{I}_{rc} - \mathbf{I}_{rb}} = \frac{\mathbf{V}_{r1} - \mathbf{V}_{r2}}{\mathbf{I}_{r1} - \mathbf{I}_{r2}} = \frac{\mathbf{V}_{ry}}{\mathbf{I}_{ry}} \tag{a}$$

$$\mathbf{Z}_{ac} = \frac{\mathbf{V}_{rB}}{\mathbf{I}_{rB}} = \frac{\mathbf{V}_{ra} - \mathbf{V}_{rc}}{\mathbf{I}_{ra} - \mathbf{I}_{rc}} = \frac{\mathbf{V}_{r1} - \mathbf{a}^2\mathbf{V}_{r2}}{\mathbf{I}_{r1} - \mathbf{a}^2\mathbf{I}_{r2}} = \frac{\sqrt{3}\,\mathbf{V}_{rx} - \mathbf{V}_{ry}}{\sqrt{3}\,\mathbf{I}_{rx} - \mathbf{I}_{ry}} \tag{b}$$

$$\mathbf{Z}_{ba} = \frac{\mathbf{V}_{rC}}{\mathbf{I}_{rC}} = \frac{\mathbf{V}_{rb} - \mathbf{V}_{ra}}{\mathbf{I}_{rb} - \mathbf{I}_{ra}} = \frac{\mathbf{V}_{r1} - \mathbf{a}\mathbf{V}_{r2}}{\mathbf{I}_{r1} - \mathbf{a}\mathbf{I}_{r2}} = \frac{\sqrt{3}\,\mathbf{V}_{rx} + \mathbf{V}_{ry}}{\sqrt{3}\,\mathbf{I}_{rx} + \mathbf{I}_{ry}} \tag{c}$$

Here subscript r refers to the relay location; A, B, and C, to the delta voltages and currents; a, b, and c, to the phase, or Y, voltages and currents; 1 and 2, to their symmetrical components; and x and y, to their two-phase coordinates.

(*a*) *Fault present.* The line-to-line fault on phases b and c is represented in two-phase coordinates by grounding point F on the y network and leaving it ungrounded on the x network. Both x and y networks are identical with the positive-sequence network (Fig. 14), except that in the y network the phase of the e.m.f.'s is advanced by 90°.

Relay on faulted phase. It was shown in Chapter IX that, during any fault (except line-to-ground) on the line and phases that the relay is intended to protect, the impedance seen by the relay operating on delta current and voltage is the positive-sequence impedance between the relay and the fault. This is $50\angle 80^\circ$ ohms in the present example. The same conclusion can be reached from inspection of eq. a and of the y network (Fig. 14) with point F grounded. Since this impedance is independent of the values of $\mathbf{E}_A$ and $\mathbf{E}_B$, the impedance chart reduces to a single point, shown as $\mathbf{Z}_{cb}$ on Fig. 17 (p. 186).

Relays on unfaulted phases. The values of $\mathbf{V}_{rx}$, $\mathbf{I}_{rx}$, $\mathbf{V}_{ry}$, and $\mathbf{I}_{ry}$ are needed for three conditions: (1) $\mathbf{E}_A = 0$, (2) $\mathbf{E}_B = 0$, (3) $\mathbf{E}_A = \mathbf{E}_B$. These values, found by inspection of the circuit diagram, are listed in Table 6.

TABLE 6

VOLTAGES AND CURRENTS AT THE RELAY LOCATION R (FIG. 14) UNDER THREE CONDITIONS, FOR DETERMINATION OF $\mathbf{Z}_A$, $\mathbf{Z}_B$, AND $\mathbf{Z}_K$

(EXAMPLE 3)

	$\mathbf{E}_A = 0$	$\mathbf{E}_B = 0$	$\mathbf{E}_A = \mathbf{E}_B$
$\mathbf{V}_{rx}$	$\frac{20}{100}\mathbf{E}_B$	$\frac{80}{100}\mathbf{E}_A$	$\mathbf{E}_A$
$\mathbf{V}_{ry}$	0	$\frac{50}{70}j\mathbf{E}_A$	$\frac{50}{70}j\mathbf{E}_A$
$\mathbf{I}_{rx}$	$\dfrac{-\mathbf{E}_B}{100\angle 80^\circ}$	$\dfrac{\mathbf{E}_A}{100\angle 80^\circ}$	0
$\mathbf{I}_{ry}$	0	$\dfrac{j\mathbf{E}_A}{70\angle 80^\circ}$	$\dfrac{j\mathbf{E}_A}{70\angle 80^\circ}$

Relay ac. By eq. *b*, the impedance seen by this relay is

$$\mathbf{Z}_{ac} = \frac{\sqrt{3}\,\mathbf{V}_{rx} - \mathbf{V}_{ry}}{\sqrt{3}\,\mathbf{I}_{rx} - \mathbf{I}_{ry}}$$

For the three conditions of Table 6 this takes the following values: For $\mathbf{E}_A = 0$, it is:

$$\mathbf{Z}_A = \frac{\sqrt{3} \times 0.20\mathbf{E}_B - 0}{-\sqrt{3} \times 0.01\mathbf{E}_B\angle -80^\circ - 0} = 20\angle 260^\circ = -3.5 - j19.7 \text{ ohms}$$

For $\mathbf{E}_B = 0$, it is:

$$\mathbf{Z}_B = \frac{\sqrt{3} \times 0.80\mathbf{E}_A - j0.714\mathbf{E}_A}{\sqrt{3} \times 0.01\mathbf{E}_A\angle -80^\circ - j0.0143\mathbf{E}_A\angle -80^\circ} = \frac{1.387 - j0.714}{0.0173 - j0.0143}\angle 80^\circ$$

$$= \frac{1.560\angle -27.3^\circ\ \angle 80^\circ}{0.0224\angle -39.6^\circ} = 69.5\angle 92.2^\circ = -2.6 + j69.5 \text{ ohms}$$

For $\mathbf{E}_A = \mathbf{E}_B$, it is:

$$\mathbf{Z}_K = \frac{\sqrt{3}\,\mathbf{E}_A - j0.714\mathbf{E}_A}{\sqrt{3} \times 0 - j0.0143\mathbf{E}_A\angle -80^\circ} = \frac{1.732 - j0.714}{-j0.0143}\angle 80^\circ$$

$$= \frac{1.872\angle -22.4^\circ\ \angle 80^\circ}{0.0143\angle -90^\circ} = 131.2\angle 147.6^\circ = -110.5 + j70.4 \text{ ohms}$$

By eq. 5,

$$\mathbf{K} = \frac{\mathbf{Z}_K - \mathbf{Z}_A}{\mathbf{Z}_K - \mathbf{Z}_B} = \frac{(-110.5 + j70.4) - (-3.5 - j19.7)}{(-110.5 + j70.4) - (-2.6 + j69.5)}$$

$$= \frac{-107.0 + j90.1}{-107.9 - j0.9} = \frac{140\underline{/140^\circ}}{108\underline{/180.5^\circ}} = 1.295\underline{/-39.5^\circ}$$

$$\approx 1.30\underline{/-40^\circ}$$

The impedance chart for relay *ac* under fault conditions has its poles *A* and *B* at $20\underline{/260^\circ}$ and $69.5\underline{/92.2^\circ}$ ohms, respectively. The labels on the magnitude circles of the general impedance chart should be divided by 1.30, and those on the angle arcs should be increased by 40°. The distance between poles is

$$AB = |\mathbf{Z}_B - \mathbf{Z}_A| = |0.9 + j89.2| = 89.2 \text{ ohms}$$

The chart of Fig. 15 was constructed in per unit with a base impedance equal to 89.2 ohms. On this base, $\mathbf{Z}_A = 0.224\underline{/260^\circ} = -0.039 - j0.221$ per unit, and $\mathbf{Z}_B = 0.779\underline{/92.2^\circ} = -0.029 + j0.779$ per unit. To construct the chart, these points *A* and *B* are located at coordinates $\mathbf{Z}_A$ and $\mathbf{Z}_B$, and line *AB* is drawn through them. At the midpoint *M* of *AB* (Fig. 12), line *GMH* is drawn perpendicular to *AB*. Values of E_A/E_B covering the operating voltage range are selected, and values of $KE_A/E_B = 1.30\ E_A/E_B$ are calculated. The lengths of the radii *r* and the distances *MX* from *M* to the intersections *X* of the circles for constant values of KE_A/E_B with the line *AB* are read from Table 4. For example, if $E_A/E_B = 1$, $KE_A/E_B = 1.30$; and, from Table 4, with $AB = 1$, $r = 1.884$, and $MX = 0.065$. In Fig. 15 this circle is drawn. The straight line for $KE_A/E_B = 1$ is also shown; it corresponds to $E_A/E_B = 1/1.30 = 0.77$.

In Table 5 the distance MC' of the center of the arc for any constant value of δ can be read at $\phi = \delta - 40^\circ$. For example, for $\delta = 10^\circ$, $\phi = 10^\circ - 40^\circ = 330^\circ$, and from Table 5, $MC' = -0.866$. (The negative sign indicates that it is laid off from *M* toward *G*, Fig. 12.) The circle is drawn with center at C' and with such radius that the circle passes through poles *A* and *B*. The longer arc between *A* and *B* is for $\delta = 10^\circ$; the shorter arc, for $\delta = 190^\circ$. The line *AB* is for $\phi = 180^\circ$, or $\delta = 220^\circ$. The extensions of line *AB* are for $\phi = 0$, or $\delta = 40^\circ$. These and other values of δ are indicated in Fig. 15.

Relay ba. By eq. *c*, the impedance of this relay is

$$\mathbf{Z}_{ba} = \frac{\sqrt{3}\,\mathbf{V}_{rx} + \mathbf{V}_{ry}}{\sqrt{3}\,\mathbf{I}_{rx} + \mathbf{I}_{ry}}$$

which is like that for relay *ac* except for the signs of the second terms of numerator and denominator. For the three conditions previously considered,

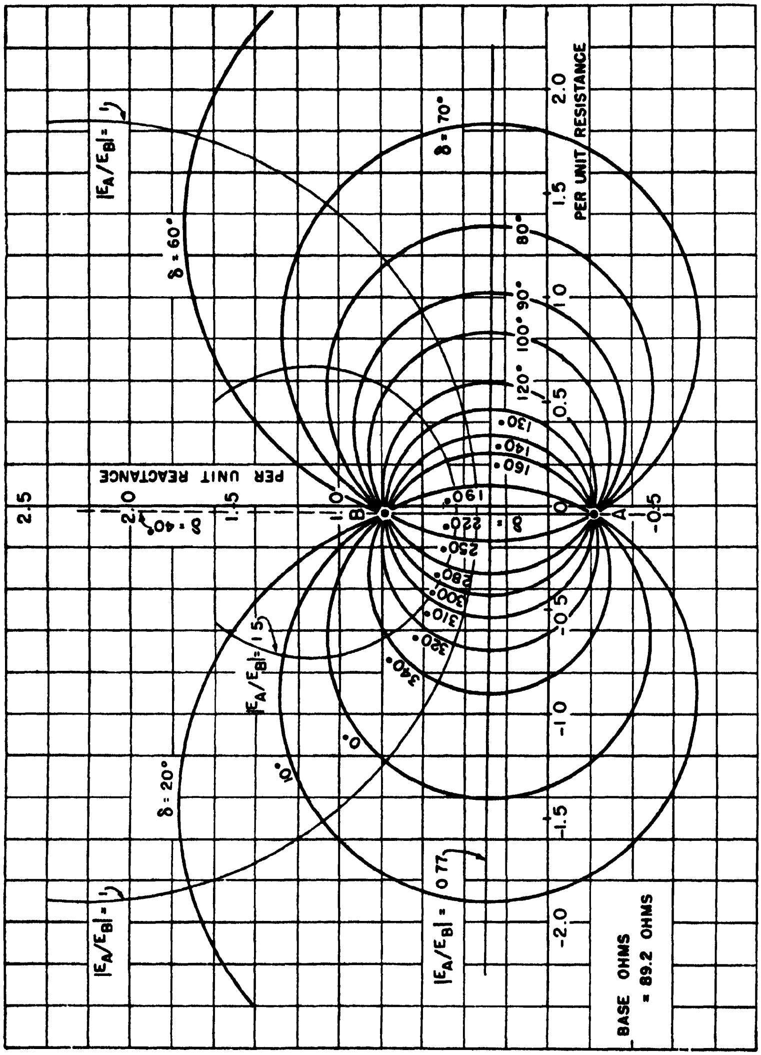


FIG. 15. Chart of Z_{ac}, the impedance seen by relay *ac* during line-to-line fault (Example 3). (From Ref. 17 by permission)

this impedance becomes successively:

$$\mathbf{Z}_A = 20\underline{/260^\circ} = -3.5 - j19.7 \text{ ohms}$$

$$\mathbf{Z}_B = \frac{1.387 + j0.714}{0.0173 + j0.0143}\underline{/80^\circ} = \frac{1.560\underline{/27.3^\circ}\,\underline{/80^\circ}}{0.0224\underline{/39.6^\circ}}$$

$$= 69.5\underline{/67.7^\circ} = 26.5 + j64.2 \text{ ohms}$$

$$\mathbf{Z}_K = \frac{1.732 + j0.714}{j0.0143}\underline{/80^\circ} = \frac{1.872\underline{/22.4^\circ}\,\underline{/80^\circ}}{0.0143\underline{/90^\circ}}$$

$$= 131.2\underline{/12.4^\circ} = 128.2 + j28.2 \text{ ohms}$$

By eq. 5,

$$\mathbf{K} = \frac{(128.2 + j28.2) - (-3.5 - j19.7)}{(128.2 + j28.2) - (26.5 + j64.2)}$$

$$= \frac{131.7 + j47.9}{101.7 - j36.0} = \frac{140\underline{/20^\circ}}{108\underline{/-19.5^\circ}} = 1.295\underline{/39.5^\circ}$$

$$\approx 1.30\underline{/40^\circ}$$

The impedance chart for relay *ba* under fault conditions has its poles at $-3.5 - j19.7$ and $26.5 + j64.2$ ohms. The distance between poles is

$$AB = |\mathbf{Z}_B - \mathbf{Z}_A| = |30.0 + j83.9| = 89.2 \text{ ohms}$$

the same as for relay *ac*. In per unit of 89.2 ohms, the poles are at $-0.039 - j0.221$ and $0.297 + j0.720$.

The chart for $\mathbf{Z}_{ba}$ is given in Fig. 16, with impedances in per unit of 89.2 ohms. It was constructed by first laying out on tracing paper a coordinate grid with the unit of impedance equal to distance AB of the general chart of Fig. 12. The poles A and B were then marked at coordinates $\mathbf{Z}_A = -0.039 - j0.221$ and $\mathbf{Z}_B = 0.297 + j0.720$, which are unit distance apart. Poles A and B on the tracing paper were then placed over the corresponding points on the general chart, and certain circles were traced from the general chart. The magnitude circles were then labelled with values of E_A/E_B found by dividing the corresponding values of KE_A/E_B on the general chart by 1.30. The angle arcs were labelled with values of δ found by subtracting 40° from the corresponding values of ϕ.

(*b*) *Fault absent.* When the system is unfaulted, $\mathbf{V}_2 = 0$ and $\mathbf{I}_2 = 0$; hence the impedance seen by every relay (eqs. *a*, *b*, *c*) is the same and is

$$\mathbf{Z}_r = \frac{\mathbf{V}_{r1}}{\mathbf{I}_{r1}} \qquad (d)$$

Its values can be found directly from the positive-sequence diagram (Fig. 14)

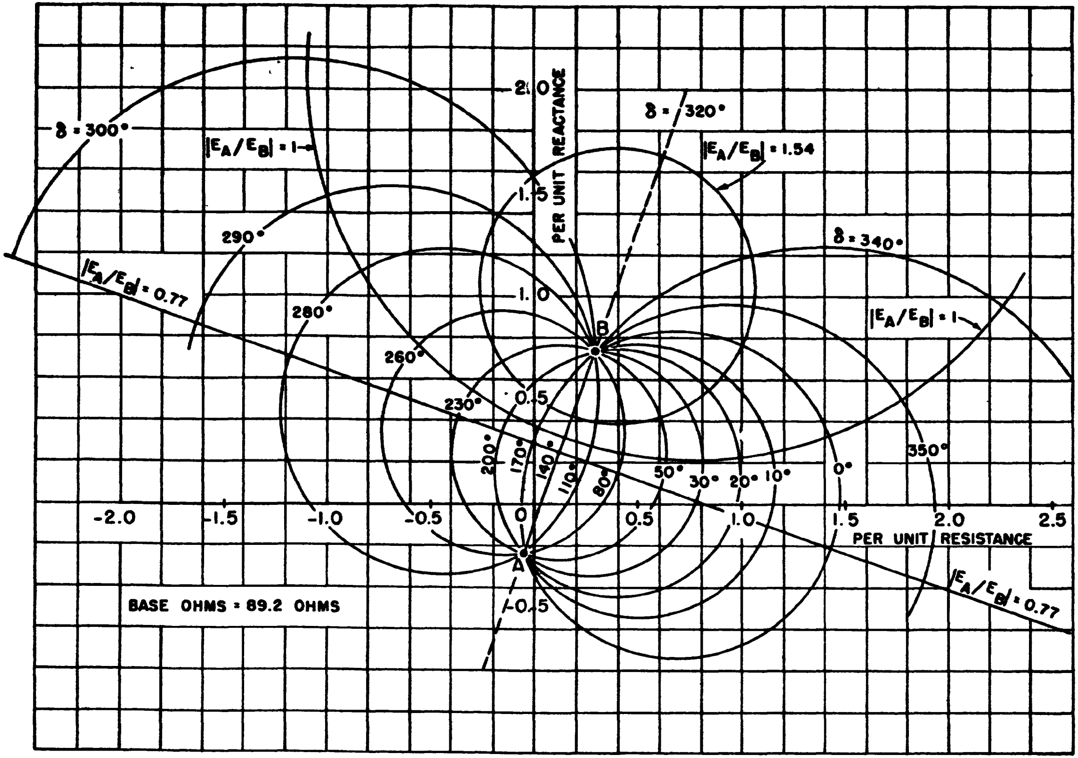


FIG. 16. Chart of Z_{ba}, the impedance seen by relay *ba* during line-to-line fault (Example 3). (From Ref. 17 by permission)

by giving $\mathbf{E}_A$ and $\mathbf{E}_B$ appropriate values. Putting $\mathbf{E}_A = 0$, we get

$$\mathbf{Z}_A = -20\underline{/80^\circ} = 20\underline{/260^\circ} \text{ ohms}$$

The negative sign is introduced because the relays are assumed to "look" toward B. Putting $\mathbf{E}_B = 0$, we get

$$\mathbf{Z}_B = 50\underline{/80^\circ} + 30\underline{/80^\circ} = 80\underline{/80^\circ} \text{ ohms}$$

Putting $\mathbf{E}_A = \mathbf{E}_B$, we get $\mathbf{I}_{r1} = 0$; hence

$$\mathbf{Z}_K = \infty$$

and therefore

$$\mathbf{K} = 1\underline{/0}$$

The chart applying to all three relays when the system is unfaulted has its poles A and B at $20\underline{/260^\circ}$ and $80\underline{/80^\circ}$ ohms, respectively, and the labelling of its circles is the same as that on the general impedance chart. In per unit of 89.2 ohms, the poles are at $-0.039 - j0.221$ and $0.156 + j0.884$.

For $E_A/E_B = 1$, the locus is the perpendicular bisector of AB. This locus (labelled $\mathbf{Z}_R$) is shown in Fig. 17, together with the point for $\mathbf{Z}_{cb}$ and the loci for $\mathbf{Z}_{ac}$ and $\mathbf{Z}_{ba}$ for $E_A/E_B = 1$ and the fault on the system.

Proof of the general swing-impedance locus. The statements made in the preceding section regarding the general swing-impedance locus will now be proved by means of the following steps:

1. It will first be shown that the impedance seen by a relay in a two-machine system can always be written in the form

$$\mathbf{Z}_r = \frac{\mathbf{K}_1\mathbf{E}_B + \mathbf{K}_2\mathbf{E}_A}{\mathbf{K}_3\mathbf{E}_B + \mathbf{K}_4\mathbf{E}_A} = \frac{\mathbf{K}_1 + \mathbf{K}_2(\mathbf{E}_A/\mathbf{E}_B)}{\mathbf{K}_3 + \mathbf{K}_4(\mathbf{E}_A/\mathbf{E}_B)} \qquad [6]$$

where $\mathbf{K}_1$, $\mathbf{K}_2$, $\mathbf{K}_3$, and $\mathbf{K}_4$ are complex constants, and $\mathbf{E}_A$ and $\mathbf{E}_B$ are the internal e.m.f.'s of the machines or any two applied voltages.

2. It will then be shown that, by means of certain mathematical operations which correspond to the graphical operations required to transform a specific impedance chart into the general impedance chart (the inverse operations for adapting the general chart to a specific case have already been described), eq. 6 can be put in the form:

$$\mathbf{Z} = \frac{1 + \mathbf{K}\mathbf{E}_A/\mathbf{E}_B}{1 - \mathbf{K}\mathbf{E}_A/\mathbf{E}_B} = \frac{1 + \mathbf{W}}{1 - \mathbf{W}} \qquad [7]$$

where $\mathbf{K} = -\mathbf{K}_4/\mathbf{K}_3$ and $\mathbf{W} = \mathbf{K}\mathbf{E}_A/\mathbf{E}_B$.

3. Finally, it will be shown that the loci, in the $\mathbf{Z}$ plane, of constant magnitude and of constant angle of $\mathbf{W}$ are two orthogonal

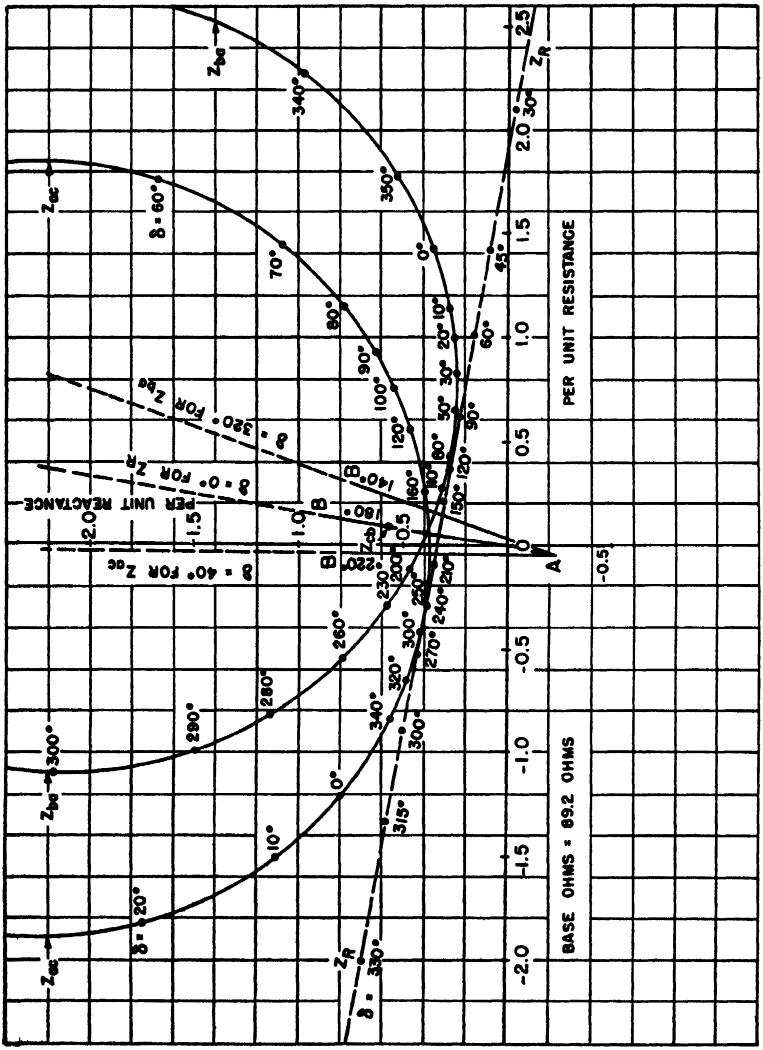


FIG. 17. Chart of Z_{cb}, Z_{ac}, and Z_{bc} for line-to-line fault and of Z_R with no fault. Base impedance is 89.2 ohms. (From Ref. 17 by permission)

sets of circles called the *bipolar circles*. Expressions for the radii and for the coordinates of the centers of these circles will be derived. The poles are at $\mathbf{Z} = \pm 1 + j0$.

1. In the proof that the impedance seen by a relay can be written in the form of eq. 6, first consider a balanced three-phase network (either an unfaulted network or one having a three-phase fault), so that only the positive-sequence network need be used. Also assume that the relay operates on positive-sequence voltage and current or the equivalent. The positive-sequence network can be reduced, by methods treated in Chapter III (Vol. I), until all nodes are eliminated except the following five: (1 and 2) the points immediately on each side of the relay location; (3 and 4) the two points where the e.m.f.'s of the generators are applied (points behind transient reactance); and (5) the neutral point. The equations for terminal currents in terms of terminal voltages are of the form:

$$\mathbf{I}_1 = \mathbf{Y}_{11}\mathbf{V}_1 + \mathbf{Y}_{12}\mathbf{V}_2 + \mathbf{Y}_{13}\mathbf{V}_3 + \mathbf{Y}_{14}\mathbf{V}_4 \qquad [8]$$

$$\mathbf{I}_2 = \mathbf{Y}_{21}\mathbf{V}_1 + \mathbf{Y}_{22}\mathbf{V}_2 + \mathbf{Y}_{23}\mathbf{V}_3 + \mathbf{Y}_{24}\mathbf{V}_4 \qquad [9]$$

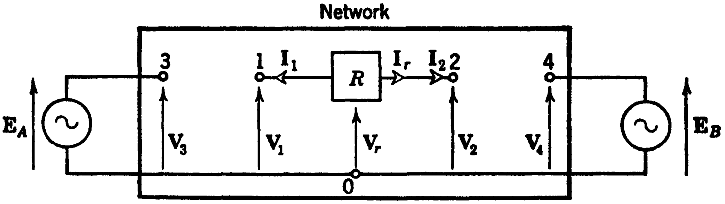


FIG. 18. Five-terminal linear network used in the proof that the swing-impedance locus is a circle or straight line.

and similarly for $\mathbf{I}_3$ and $\mathbf{I}_4$. The terminal conditions are as follows (see Fig. 18): At the relay location,

$$\mathbf{V}_1 = \mathbf{V}_2 = \mathbf{V}_r \qquad [10]$$

and

$$-\mathbf{I}_1 = \mathbf{I}_2 = \mathbf{I}_r \qquad [11]$$

where $\mathbf{V}_r$ and $\mathbf{I}_r$ are the relay voltage and current, respectively. At the generators,

$$\mathbf{V}_3 = \mathbf{E}_A \qquad [12]$$

and

$$\mathbf{V}_4 = \mathbf{E}_B \qquad [13]$$

Substitution of the terminal conditions into eqs. 8 and 9 yields

$$-\mathbf{I}_r = (\mathbf{Y}_{11} + \mathbf{Y}_{12})\mathbf{V}_r + \mathbf{Y}_{13}\mathbf{E}_A + \mathbf{Y}_{14}\mathbf{E}_B \tag{14}$$

$$\mathbf{I}_r = (\mathbf{Y}_{21} + \mathbf{Y}_{22})\mathbf{V}_r + \mathbf{Y}_{23}\mathbf{E}_A + \mathbf{Y}_{24}\mathbf{E}_B \tag{15}$$

These equations must be solved for $\mathbf{V}_r$ and $\mathbf{I}_r$ as functions of $\mathbf{E}_A$ and $\mathbf{E}_B$. To get $\mathbf{V}_r$, add eqs. 14 and 15 and divide by the coefficient of $\mathbf{V}_r$, obtaining

$$\mathbf{V}_r = -\frac{(\mathbf{Y}_{13} + \mathbf{Y}_{23})\mathbf{E}_A + (\mathbf{Y}_{14} + \mathbf{Y}_{24})\mathbf{E}_B}{\mathbf{Y}_{11} + \mathbf{Y}_{12} + \mathbf{Y}_{21} + \mathbf{Y}_{22}} \tag{16}$$

To get $\mathbf{I}_r$, substitute eq. 16 into eq. 15, obtaining

$$\mathbf{I}_r = \left[-\frac{(\mathbf{Y}_{21} + \mathbf{Y}_{22})(\mathbf{Y}_{13} + \mathbf{Y}_{23})}{\mathbf{Y}_{11} + \mathbf{Y}_{12} + \mathbf{Y}_{21} + \mathbf{Y}_{22}} + \mathbf{Y}_{23}\right]\mathbf{E}_A + \left[-\frac{(\mathbf{Y}_{21} + \mathbf{Y}_{22})(\mathbf{Y}_{14} + \mathbf{Y}_{24})}{\mathbf{Y}_{11} + \mathbf{Y}_{12} + \mathbf{Y}_{21} + \mathbf{Y}_{22}} + \mathbf{Y}_{24}\right]\mathbf{E}_B \tag{17}$$

Equation 16 is of the form $\mathbf{V}_r = \mathbf{K}_1\mathbf{E}_B + \mathbf{K}_2\mathbf{E}_A$, and eq. 17 is of the form $\mathbf{I}_r = \mathbf{K}_3\mathbf{E}_B + \mathbf{K}_4\mathbf{E}_A$. The impedance seen by the relay, $\mathbf{Z}_r = \mathbf{V}_r/\mathbf{I}_r$, is therefore of the form of eq. 6. The admittance $\mathbf{Y}_r = 1/\mathbf{Z}_r = \mathbf{I}_r/\mathbf{V}_r$ is also of the form of eq. 6.

Next consider an unbalanced three-phase network. It can be represented by the three sequence networks, properly interconnected at the point of fault. The zero- and negative-sequence networks can be reduced and combined to a fault shunt across the positive-sequence network at this point. Then the positive-sequence voltage and current at the relay location can be found and expressed in the same manner as for an unfaulted network. The positive-sequence voltage at the point of fault can be found in similar fashion and is of the form $\mathbf{K}'\mathbf{E}_A + \mathbf{K}''\mathbf{E}_B$. Since the zero- and negative-sequence networks contain no e.m.f.'s, the zero- and negative-sequence voltages and currents at the point of fault are proportional to the positive-sequence voltage there; moreover, the zero- and negative-sequence voltages and currents at the relay location are proportional to the corresponding quantities at the point of fault, and therefore have the form $\mathbf{K}(\mathbf{K}'\mathbf{E}_A + \mathbf{K}''\mathbf{E}_B)$. Each phase voltage and current is a linear combination of symmetrical components and therefore has this same form. The impedance seen by the relay is the ratio of two such expressions and thus has the form of eq. 6. This is true both for relays on faulted phases and for those on unfaulted phases.

2. We must now show how eq. 6 can be changed into the form of eq. 7.

If the loci of $\mathbf{Z}_r$, as given by eq. 6, have the forms already described, the coordinates of the poles can be obtained by first setting $\mathbf{E}_A = 0$ and then setting $\mathbf{E}_B = 0$. For if either of these voltages is zero, δ, their phase difference, is indeterminate. This fact is shown on the chart by the circumstance that all the arcs for different constant values of δ go through both poles. Putting $\mathbf{E}_A = 0$ in eq. 6, we get

$$\mathbf{Z}_r = \mathbf{Z}_A = \frac{\mathbf{K}_1}{\mathbf{K}_3} \tag{18}$$

and, putting $\mathbf{E}_B = 0$, we get

$$\mathbf{Z}_r = \mathbf{Z}_B = \frac{\mathbf{K}_2}{\mathbf{K}_4} \tag{19}$$

The point midway between the poles is at coordinates

$$\mathbf{Z}_m = \frac{\mathbf{Z}_A + \mathbf{Z}_B}{2} = \frac{1}{2}\left(\frac{\mathbf{K}_1}{\mathbf{K}_3} + \frac{\mathbf{K}_2}{\mathbf{K}_4}\right) \tag{20}$$

and the directed distance between the poles is

$$\mathbf{D} = \mathbf{Z}_A - \mathbf{Z}_B = \frac{\mathbf{K}_1}{\mathbf{K}_3} - \frac{\mathbf{K}_2}{\mathbf{K}_4} \tag{21}$$

The point midway between the poles can be shifted to the origin by subtracting $\mathbf{Z}_m$ from the right-hand member of eq. 6. The poles can then be brought to coordinates $1 + j0$ and $-1 + j0$ by dividing the result by $\mathbf{D}/2$. Graphically, this corresponds to rotation and change of scale. These operations and the result are indicated below, with intervening algebraic steps omitted:

$$\frac{\dfrac{\mathbf{K}_1 + \mathbf{K}_2(\mathbf{E}_A/\mathbf{E}_B)}{\mathbf{K}_3 + \mathbf{K}_4(\mathbf{E}_A/\mathbf{E}_B)} - \dfrac{1}{2}\left(\dfrac{\mathbf{K}_1}{\mathbf{K}_3} + \dfrac{\mathbf{K}_2}{\mathbf{K}_4}\right)}{\dfrac{1}{2}\left(\dfrac{\mathbf{K}_1}{\mathbf{K}_3} - \dfrac{\mathbf{K}_2}{\mathbf{K}_4}\right)}$$

$$= \frac{1 - (\mathbf{K}_4/\mathbf{K}_3)(\mathbf{E}_A/\mathbf{E}_B)}{1 + (\mathbf{K}_4/\mathbf{K}_3)(\mathbf{E}_A/\mathbf{E}_B)} = \frac{1 + \mathbf{K}\mathbf{E}_A/\mathbf{E}_B}{1 - \mathbf{K}\mathbf{E}_A/\mathbf{E}_B} \tag{22}$$

where $\mathbf{K} = -\mathbf{K}_4/\mathbf{K}_3$. This result agrees with eq. 7.

The complex constant $\mathbf{K}$ is the one previously used in the description of the general impedance chart. This fact can be verified by first putting $\mathbf{E}_A = \mathbf{E}_B$ in eq. 6 to get

$$\mathbf{Z}_r = \mathbf{Z}_K = \frac{\mathbf{K}_1 + \mathbf{K}_2}{\mathbf{K}_3 + \mathbf{K}_4} \tag{23}$$

and then substituting eqs. 18, 19, and 23 into eq. 5, to obtain

$$\mathbf{K} = \frac{\mathbf{Z}_K - \mathbf{Z}_A}{\mathbf{Z}_K - \mathbf{Z}_B} = \frac{\dfrac{\mathbf{K}_1 + \mathbf{K}_2}{\mathbf{K}_3 + \mathbf{K}_4} - \dfrac{\mathbf{K}_1}{\mathbf{K}_3}}{\dfrac{\mathbf{K}_1 + \mathbf{K}_2}{\mathbf{K}_3 + \mathbf{K}_4} - \dfrac{\mathbf{K}_2}{\mathbf{K}_4}} = -\frac{\mathbf{K}_4}{\mathbf{K}_3} \tag{24}$$

The last step in transforming a specific impedance chart into the general impedance chart is to change the labelling of the circles. This is done by multiplying $\mathbf{E}_A/\mathbf{E}_B = E_A/E_B\underline{/\delta}$ by $\mathbf{K} = K\underline{/\theta_K}$ to obtain $\mathbf{K}\mathbf{E}_A/\mathbf{E}_B = KE_A/E_B\underline{/\phi}$.

3. We must now show that a chart of eq. 7 has the form of the general impedance chart. That is, the loci, in the $\mathbf{Z}$ plane, of constant magnitude or constant phase of the complex variable $\mathbf{W} = \mathbf{K}\mathbf{E}_A/\mathbf{E}_B$ must be shown to be circles, and the radii and locations of the centers of these circles must be determined.

Magnitude circles. If eq. 7 is solved for $\mathbf{W}$ as a function of $\mathbf{Z}$, the result is:

$$\mathbf{W} = \frac{\mathbf{Z} - 1}{\mathbf{Z} + 1} \tag{25}$$

Let the rectangular form of $\mathbf{Z}$ be

$$\mathbf{Z} = X + jY \tag{26}$$

and let the polar form of $\mathbf{W}$ be

$$\mathbf{W} = W\underline{/\phi} \tag{27}$$

Substitution of eq. 26 into eq. 25 gives

$$\mathbf{W} = \frac{X + jY - 1}{X + jY + 1} \tag{28}$$

The magnitude of $\mathbf{W}$, squared, is

$$W^2 = \frac{(X - 1)^2 + Y^2}{(X + 1)^2 + Y^2} \tag{29}$$

whence, by rearrangement,

$$X^2 - 2X\frac{1 + W^2}{1 - W^2} + Y^2 = -1 \tag{30}$$

Completion of the square in X gives

$$\left(X - \frac{1 + W^2}{1 - W^2}\right)^2 + Y^2 = -1 + \left(\frac{1 + W^2}{1 - W^2}\right)^2 = \left(\frac{2W}{1 - W^2}\right)^2 \tag{31}$$

This is the equation of a circle with

$$\text{center at} \quad \frac{1+W^2}{1-W^2} + j0 \tag{32}$$

and

$$\text{radius} = \frac{2W}{1-W^2} \tag{33}$$

This circle intersects the real axis at

$$\frac{1+W^2}{1-W^2} \pm \frac{2W}{1-W^2} = \frac{1 \pm 2W + W^2}{1-W^2} = \frac{(1 \pm W)^2}{(1+W)(1-W)}$$

$$= \frac{1+W}{1-W} \quad \text{and} \quad \frac{1-W}{1+W} \tag{34}$$

These two values are reciprocals.

Angle circles. By putting each side of eq. 28 in polar form and equating the angles, we get

$$\phi = \tan^{-1}\frac{Y}{X-1} - \tan^{-1}\frac{Y}{X+1} = \phi_1 - \phi_2 \tag{35}$$

By a well-known trigonometric identity,

$$\tan\phi = \tan(\phi_1 - \phi_2) = \frac{\tan\phi_1 - \tan\phi_2}{1 + \tan\phi_1 \tan\phi_2} \tag{36}$$

Hence

$$\tan\phi = \frac{\dfrac{Y}{X-1} - \dfrac{Y}{X+1}}{1 + \dfrac{Y^2}{X^2-1}} = \frac{2Y}{X^2+Y^2-1} \tag{37}$$

By rearrangement, this equation becomes

$$X^2 + Y^2 - 1 = \frac{2Y}{\tan\phi} = 2Y\cot\phi \tag{38}$$

$$X^2 + Y^2 - 2Y\cot\phi = 1 \tag{39}$$

Completion of the square in Y gives

$$X^2 + (Y - \cot\phi)^2 = 1 + \cot^2\phi = \csc^2\phi \tag{40}$$

This is the equation of a circle with

$$\text{center at} \quad 0 + j\cot\phi \tag{41}$$

and

$$\text{radius} = \csc\phi \tag{42}$$

The circle intersects the imaginary axis at

$$\cot \phi \pm \csc \phi = \cot \frac{\phi}{2} \quad \text{and} \quad -\tan \frac{\phi}{2} \tag{43}$$

These two values are *negative reciprocals.* Since $\tan \phi = \tan (\phi + 180°)$ and $\cot \phi = \cot (\phi + 180°)$, the foregoing derivation makes no distinction between the two parts of a circle for values of ϕ differing by 180°. The first expression of eq. 43, however, gives the correct intersection of any ϕ arc with the imaginary axis.

Since eq. 40 is satisfied by $X = \pm 1$, $Y = 0$ for all values of ϕ, all the angle circles pass through the two points $1 + j0$ and $-1 + j0$.

We have now shown that the loci in the impedance plane of constant magnitude of $\mathbf{KE}_A/\mathbf{E}_B$ are circles and that the loci of constant angle of $\mathbf{KE}_A/\mathbf{E}_B$ are other circles. Expressions for the radii, coordinates of the centers, and intercepts of all these circles have been derived, thus enabling one to draw the general chart. Tables 4 and 5 (pp. 177 and 178) list numerical values of these quantities.

The effect of shunt capacitance on the impedance loci. In the study of carrier-pilot relays during out-of-step conditions, it is found convenient to superpose the impedance diagrams of the relays at the two ends of the protected line. If the line between the two relay locations consists solely of series impedance (which is very nearly true for short unfaulted lines with no tapped load), then the impedance seen by the relays at one location differs from the impedance seen by the relays at the other location precisely by the amount of this series impedance. The reason is that the currents at the two locations are equal, whereas the voltages differ by the product of the current and the line impedance. As a result, the swing-impedance locus at one location differs from that at the other location by a constant: regardless of whether the locus is a circle or a straight line, all points on it are shifted the same amount. Therefore, the same locus can be used for both locations if it is interpreted with respect to origins which differ by the line impedance. In addition, one set of coordinates should be reversed to take into account the difference in connections of the relays at the two ends of a line to give opposite tripping directions. With this change in sign of one impedance, the *sum* of the impedances seen from the two locations is constant, instead of the *difference.*

When there is a three-phase short circuit on a line consisting solely of series impedance, the impedance seen from each end is the positive-sequence impedance of the line from the relay to the short circuit, so again the sum of the impedances seen from the two ends is a constant equal to the impedance of the protected line. The same thing is true with regard to the relays on the faulted phase during line-to-line or two-line-to-ground short circuits, provided that the relays operate on delta currents and voltages. Therefore a single fault-impedance locus, as well as a single swing-impedance locus can be used in connection with both relays, provided that the origins of coordinates for the two differ by the line impedance.

On the other hand, if the protected line has appreciable shunt capacitance (which is true for overhead lines over, perhaps, 150 miles long), the swing-impedance loci are appreciably altered, and the loci for the two ends no longer coincide when plotted with superposed coordinates as described above. The effect of shunt capacitance is to bend the loci apart. This may be shown qualitatively, as follows: In Fig. 4, the locus for $E_A/E_B = 1$, with capacitance neglected, is a straight line. If capacitance is considered, and if E_A and E_B are in phase ($\delta = 0$), charging current flows from both ends of the line toward the center, and the impedance looking toward the center from any other point is principally capacitive (negative) reactance. Therefore the locus must intersect the negative X axis. The point on the locus for $\delta = 180°$ is affected but little by the addition of capacitance. Thus, the effect of capacitance is to bend the locus, originally a straight line, downward at the sides to become a circle surrounding the origin. This is true at both ends of the line. Therefore, if the loci of impedances seen from the two ends of the line are superposed, as before, they no longer coincide, but each becomes a circle surrounding its origin of coordinates, as shown in Fig. 19. Loci for other values of E_A/E_B are likewise bent toward the respective origins. For example, a circle for a large value of E_A/E_B, which lies above the straight line and surrounds N, has its diameter increased by capacitance when viewed from M, and decreased when viewed from N. Since the loci viewed from M and N no longer coincide, some of the advantage of plotting them on the same diagram has been lost. Nevertheless, if the two loci do not diverge greatly in the region of principal interest, a single point on the diagram still represents approximately the impedances seen by the relays at both ends for the same values of δ.

Shunt capacitance affects not only the swing-impedance loci but also the fault-impedance locus. The impedance seen during a fault is no longer proportional to the distance d to the fault, but rather to $\tanh \gamma d$, where γ is the propagation constant. The sum of the impedances seen from the two ends is not constant. Thus the scale of d becomes somewhat nonuniform for long lines, and different scales should be used for each end. If MN in Fig. 19 represents the impedance seen when there is a short circuit at the far end, a short circuit near the middle of the line appears as *Mm* from one end and *Nn* from the other.

A quantitative study of the effect of distributed shunt capacitance on the swing- and fault-impedance loci can be made by use of the equivalent T or π circuit of the line or by use of its general circuit constants. Using the latter, Poage, Streifus, MacGregor, and George[10] have shown that the locus of the input impedance of an electrically long line with receiving-end and sending-end voltages of constant magnitude is a circle (or straight line), and they have derived the following expressions for the center and radius of the circle:

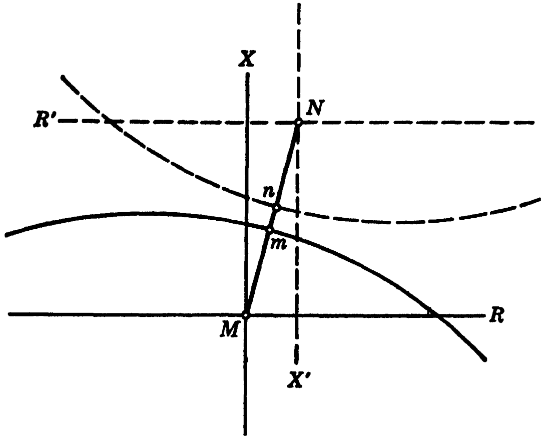


FIG. 19. Loci of swing and fault impedances viewed from the two ends of a transmission line having appreciable shunt capacitance. The solid circle is the swing impedance seen from *M*, the broken circle is that seen from *N*, and *MN* is the locus of fault impedances seen from either end.

$$\text{Center at}\quad \mathbf{Z}_s = \frac{BD\underline{/\beta - \Delta}}{D^2 - \left(\frac{E_r}{E_s}\right)^2} \qquad [44]$$

$$\text{Radius} = \left| \frac{B\left(\frac{E_r}{E_s}\right)}{D^2 - \left(\frac{E_r}{E_s}\right)^2} \right| \qquad [45]$$

where $\mathbf{B} = B\underline{/\beta}$ and $\mathbf{D} = D\underline{/\Delta}$ are two of the four general circuit constants (**A, B, C, D**) of the line (including transformers at one or both ends, if desired), and E_r/E_s is the magnitude of the ratio of sending-end, or near-end, voltage to receiving-end, or far-end, voltage.

The derivation of eqs. 44 and 45 is as follows: The receiving-end voltage $\mathbf{E}_r$ of any four-terminal network is given in terms of the sending-end voltage and current, $\mathbf{E}_s$ and $\mathbf{I}_s$, by the equation:

$$\mathbf{E}_r = \mathbf{D}\mathbf{E}_s - \mathbf{B}\mathbf{I}_s \qquad [46]$$

Solved for $\mathbf{I}_s$, it becomes:

$$\mathbf{I}_s = \frac{\mathbf{D}\mathbf{E}_s - \mathbf{E}_r}{\mathbf{B}} \qquad [47]$$

The sending-end admittance is

$$\mathbf{Y}_s = \frac{\mathbf{I}_s}{\mathbf{E}_s} = \frac{\mathbf{D} - \dfrac{\mathbf{E}_r}{\mathbf{E}_s}}{\mathbf{B}} = \frac{D}{B}\underline{/\Delta - \beta} - \frac{1}{B}\left(\frac{E_r}{E_s}\right)\underline{/-\delta_{rs} - \beta} \qquad [48]$$

where δ_{rs} is the angle by which $\mathbf{E}_s$ leads $\mathbf{E}_r$. The locus of $\mathbf{Y}_s$ as δ_{rs} varies is a circle with center at the point given by the first term and a rotating radius given by the second term. The sending-end impedance is

$$\mathbf{Z}_s = \frac{1}{\mathbf{Y}_s} = \frac{1}{\dfrac{\mathbf{D}}{\mathbf{B}} - \dfrac{1}{\mathbf{B}}\left(\dfrac{\mathbf{E}_r}{\mathbf{E}_s}\right)} \qquad [49]$$

This equation has the form of eq. 6 with $\mathbf{E}_A = \mathbf{E}_s$, $\mathbf{E}_B = \mathbf{E}_r$, $\mathbf{K}_1 = 0$, $\mathbf{K}_2 = 1$, $\mathbf{K}_3 = -1/\mathbf{B}$, and $\mathbf{K}_4 = \mathbf{D}/\mathbf{B}$. The poles are at $\mathbf{Z}_s = 0$ and $\mathbf{B}/\mathbf{D}$. It can be put in the form of eq. 7 by subtracting $\mathbf{B}/2\mathbf{D}$ and dividing by $-\mathbf{B}/2\mathbf{D}$. For constant $W = DE_s/E_r$, the locus is a circle, the location of the center of which can be found from eq. **32.** The value so found must be multiplied by $-\mathbf{B}/2\mathbf{D}$ and then increased by the addition of $\mathbf{B}/2\mathbf{D}$ in order to counteract the previous subtraction and division. The result is eq. 44. The radius is given by eq. 33, which must then be multiplied by $B/2D$ to obtain eq. 45.

The impedance circle may be plotted from a knowledge of its center and radius. In order to mark on this circle the points corresponding to given values of δ_{rs}, the constant-δ_{rs} circles can be constructed from their centers and radii given by eqs. 41 and 42 with $\phi = \Delta + \delta_{rs}$ and the modifications noted above. An easier way, however, is to compute the admittance by eq. 48 and then to draw straight lines through the origin, making angles with the horizontal axis which are the negatives of the corresponding admittance angles. These lines will intersect the impedance circle at the desired points.‡

If $E_r/E_s = D$, the admittance locus is a circle passing through the origin and the impedance locus is a straight line which is the perpendicular bisector of the line from the origin to point **B**/**D** (which represents the sending-end impedance with a short circuit at the receiving end). Since $D < 1$, $E_r < E_s$. With capacitance neglected, the impedance locus for $E_r = E_s$ was a straight line, and for $E_r < E_s$ it was a circle above this line. The inference that the effect of shunt capacitance is to bend the locus downward at the sides is thus confirmed.

EXAMPLE 4

A 270-mile 154-kv. line,[10] including transformers at both ends, has the following general circuit constants, referred to 154 kv.:

$$\mathbf{A} = 0.824\,\underline{/3.25^\circ}$$

$$\mathbf{B} = 282\,\underline{/77.3^\circ}\text{ ohms}$$

$$\mathbf{C} = 1{,}337 \times 10^{-6}\,\underline{/90.9^\circ}\text{ mhos}$$

$$\mathbf{D} = 0.769\,\underline{/3.56^\circ}$$

Plot (*a*) the near-end impedance circle for $E_r/E_s = 1$, marking thereon the values of δ_{rs} at 30° intervals; (*b*) the point representing the input impedance of the line with a short circuit at the far end; and (*c*) the far-end impedance circle.

Solution. (*a*) By eq. 44, the center of the near-end impedance circle is at

$$\frac{BD}{D^2 - \left(\dfrac{E_r}{E_s}\right)^2}\,\underline{/\beta - \Delta} = \frac{282 \times 0.769}{(0.769)^2 - (1)^2}\,\underline{/77.3^\circ - 3.6^\circ}$$

$$= \frac{217}{0.591 - 1.000}\,\underline{/73.7^\circ} = \frac{217}{-0.409}\,\underline{/73.7^\circ}$$

$$= 530\,\underline{/253.7^\circ} = -150 - j510\text{ ohms}$$

and by eq. 45 the radius is

$$\left|\frac{B\dfrac{E_r}{E_s}}{D^2 - \left(\dfrac{E_r}{E_s}\right)^2}\right| = \frac{282 \times 1}{0.409} = 690\text{ ohms}$$

---

‡Another graphical method of locating the δ_{rs} points on the impedance circle was presented by D. M. MacGregor in discussion of Ref. 10.

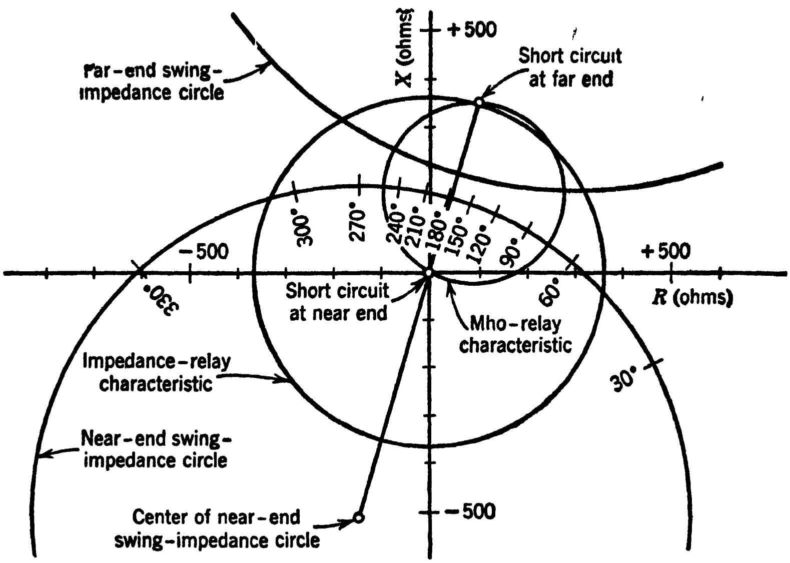

X (ohms)
+500
Short circuit at far end
Far-end swing-impedance circle
300°
270°
240°
210°
180°
150°
120°
90°
−500
+500
330°
Short circuit at near end
60°
R (ohms)
Mho-relay characteristic
Impedance-relay characteristic
30°
Near-end swing-impedance circle
Center of near-end swing-impedance circle
−500

FIG. 20. Swing-impedance locus of 270-mile 154-kv. line, including terminal transformers, with $E_r = E_s$ (Example 4).[10]

To locate points on the impedance circle for specific values of δ_{rs}, and also as a check on the circle itself, the admittance will be calculated by eq. 48 for these values of δ_{rs}, and the impedance will then be calculated as the reciprocal of the admittance. By eq. 48,

$$\begin{aligned}\mathbf{Y}_s &= \frac{D}{B}\,\underline{/\Delta - \beta} - \frac{1}{B}\left(\frac{E_r}{E_s}\right)\underline{/-\delta_{rs} - \beta} \\ &= \frac{0.769}{282}\,\underline{/3.6^\circ - 77.3^\circ} - \frac{1}{282} \times 1\,\underline{/-\delta_{rs} - 77.3^\circ} \\ &= 0.00273\,\underline{/-73.7^\circ} - 0.00354\,\underline{/-\delta_{rs} - 77.3^\circ} \\ &= 0.00077 - j0.00262 - 0.00354\,\underline{/-\delta_{rs} - 77.3^\circ}\text{ mho}\end{aligned}$$

Computation of $\mathbf{Y}_s$ and $\mathbf{Z}_s$ is carried out in Table 7. The impedance circle is plotted in Fig. 20.

(*b*) The input impedance of the line with a short circuit at the far end is found by putting $\mathbf{E}_r = 0$ in eq. 49. It is

$$\mathbf{Z} = \frac{\mathbf{B}}{\mathbf{D}} = \frac{282\,\underline{/77.3^\circ}}{0.769\,\underline{/3.6^\circ}} = 367\,\underline{/73.7^\circ} = 103 + j352\text{ ohms}$$

This point is also plotted in Fig. 20.

Note that an impedance-relay element, set to reach just to the far end of the line (including transformers), would trip for normal-load conditions if δ_{rs} exceeded about $\pm 50^\circ$.

TABLE 7

COMPUTATION OF SWING ADMITTANCE AND IMPEDANCE LOCI

(EXAMPLE 4)

(1) δ_{rs}	(2) $-\delta_{rs} - 77.3^\circ$	(3) $3.54\,\underline{/-\delta_{rs} - 77.3^\circ}$	(4) $1{,}000\mathbf{Y}_s = 0.77 - j2.62 -$ col. 3	(5) $\mathbf{Z}_s = \frac{1}{\mathbf{Y}_s}$ (ohms)
0°	−77.3°	$+0.78 - j3.45$	$-0.01 + j0.83 = 0.83\,\underline{/90.7^\circ}$	$1{,}205\,\underline{/269.3^\circ} = -15 - j1{,}205$
30°	252.7°	$-1.06 - j3.38$	$+1.83 + j0.76 = 1.98\,\underline{/22.6^\circ}$	$505\,\underline{/337.4^\circ} = +466 - j194$
60°	222.7°	$-2.60 - j2.40$	$+3.37 - j0.22 = 3.38\,\underline{/356.3^\circ}$	$296\,\underline{/3.7^\circ} = +295 + j19$
90°	192.7°	$-3.45 - j0.78$	$+4.22 - j1.84 = 4.61\,\underline{/336.4^\circ}$	$217\,\underline{/23.6^\circ} = +199 + j87$
120°	162.7°	$-3.38 + j1.06$	$+4.15 - j3.68 = 5.55\,\underline{/318.5^\circ}$	$180\,\underline{/41.5^\circ} = +135 + j120$
150°	132.7°	$-2.40 + j2.60$	$+3.17 - j5.22 = 6.10\,\underline{/301.2^\circ}$	$164\,\underline{/58.8^\circ} = +85 + j140$
180°	102.7°	$-0.78 + j3.45$	$+1.55 - j6.07 = 6.27\,\underline{/284.3^\circ}$	$159.5\,\underline{/75.7^\circ} = +39 + j155$
210°	72.7°	$+1.06 + j3.38$	$-0.29 - j6.00 = 6.00\,\underline{/267.2^\circ}$	$167\,\underline{/92.8^\circ} = -8 + j167$
240°	42.7°	$+2.60 + j2.40$	$-1.83 - j5.02 = 5.35\,\underline{/250.0^\circ}$	$187\,\underline{/110.0^\circ} = -64 + j176$
270°	12.7°	$+3.45 + j0.78$	$-2.68 - j3.40 = 4.33\,\underline{/231.8^\circ}$	$231\,\underline{/128.2^\circ} = -145 + j180$
300°	−17.3°	$+3.38 - j1.06$	$-2.61 - j1.56 = 3.04\,\underline{/210.9^\circ}$	$329\,\underline{/149.1^\circ} = -282 + j169$
330°	−47.3°	$+2.40 - j2.60$	$-1.63 - j0.02 = 1.63\,\underline{/180.7^\circ}$	$613\,\underline{/179.3^\circ} = -613 + j8$

(*c*) Expressions for the center and radius of the far-end impedance circle are found by replacing $D\underline{/\Delta}$ with $A\underline{/\alpha}$ and by interchanging E_s and E_r in eqs. 44 and 45. Hence, for $E_s = E_r$, the radius is

$$\left|\frac{B}{A^2 - 1}\right| = \frac{282}{|(0.824)^2 - 1|} = \frac{282}{|0.679 - 1|} = \frac{282}{0.321} = 878 \text{ ohms}$$

and the center is at

$$\mathbf{Z}_r = \frac{AB\underline{/\beta - \alpha}}{A^2 - 1} = -0.824 \times 878\underline{/77.3° - 3.2°} = 724\underline{/254.1°} = -198 - 696 \text{ ohms}$$

Let the coordinates in which $\mathbf{Z}_r$ is expressed be shifted from *M* to *N* and reversed as in Fig. 19. Then the center of the far-end impedance circle is at

$$103 + j352 + 198 + j696 = 301 + j1{,}048 \text{ ohms}$$

This circle also is plotted in Fig. 20. Note that the near-end and far-end swing-impedance circles curve away from each other because of the effect of shunt capacitance and fail to touch at the closest points by about 50 ohms.

Prevention of tripping during swings. The means of preventing tripping of sound lines during swings and out-of-step conditions fall into two main categories, depending upon the object to be attained: (1) In some cases it is desired to prevent tripping during swings from which the power system will recover, yet to allow tripping as soon as the system goes out of step. (2) In other cases it is desired to prevent tripping even during out-of-step conditions. The means of accomplishing the first object are discussed in this section; the second object, in the next section. The discussion concerns distance relays and carrier-pilot relays using distance elements.

If it is desired to prevent tripping during swings from which the power system will recover and yet to allow tripping during out-of-step operation, it is necessary to restrict the tripping area of the relay characteristic (plotted in the impedance plane) to a range of angles on the swing-impedance locus which is reached only during out-of-step conditions. In other words, the maximum angular separation of the machines which is likely to occur without loss of synchronism should be estimated for power flow in each direction (a typical value is ±120°), and then the relays should be so designed that their tripping areas do not include any part of the swing-impedance locus that lies in the stable range. The tripping area must be wide enough to include fault resistance. It cannot be too narrow for tripping when synchronism is lost because then the angle between machines goes through all possible values.

The width of the tripping area along the swing-impedance loci varies with the kind of distance relay used. In Fig. 21 there are plotted the tripping characteristics of three different kinds of distance relays, all set to reach the same distance. (This distance is taken as 90% of the length of the protected line section *MN*, as would be appropriate for first-zone protection.) The semicircle drawn in solid line represents a directional impedance relay; the circular segment drawn in dot-and-dash line represents a reactance element supervised by a directional starting element; and the circle drawn in dashed line represents a "mho" relay. A modified impedance relay may have a characteristic like that of the mho relay or one between those of the mho relay and the plain impedance relay. It is apparent from Fig. 21 that the angular range intercepted by the mho-relay characteristic along any swing-impedance locus is smaller than the range along the same locus intercepted by either the impedance-relay characteristic or the reactance-relay characteristic. The maximum width of the mho circle along the swing loci is the diameter of the circle; the maximum width of the impedance-relay characteristic is nearly the diameter of the impedance circle, which is twice that of the mho circle of equal reach along line *MN*; and the maximum width of the reactance-relay characteristic is nearly the diameter of the starting-element circle, which is determined by the third-zone reach and which may therefore be greater than the diameter of the first- or second-zone impedance circle. Because the mho and modified impedance relays cover a smaller angular range than plain impedance or reactance relays set to have the same reach for faults, they may be used successfully on some lines where plain impedance or reactance relays would trip during swings.

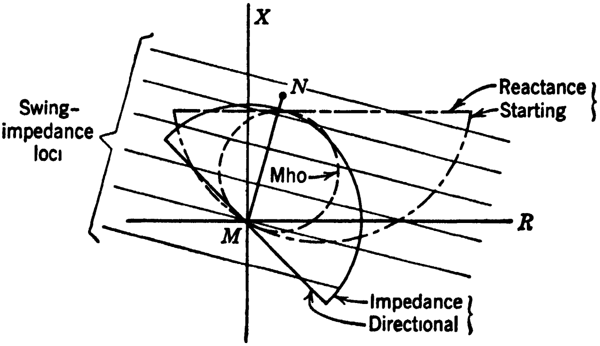


FIG. 21. Tripping characteristics of three kinds of distance relays set to reach the same distance (90% of the length of protected section *MN*).

The mho relay, despite its superiority to impedance and reactance relays in this respect, may still cover too wide an angular range to avoid tripping of long lines during swings. If swings up to ±120° are to be permitted, the mho relay is satisfactory for lines the impedance of which does not exceed about half the entire impedance between the internal voltages of the two generators.[14] This may be shown as follows: Figure 2 and eq. 4 show that the impedance represented by the distance between the 120° and 240° lines is 0.58*Z*.

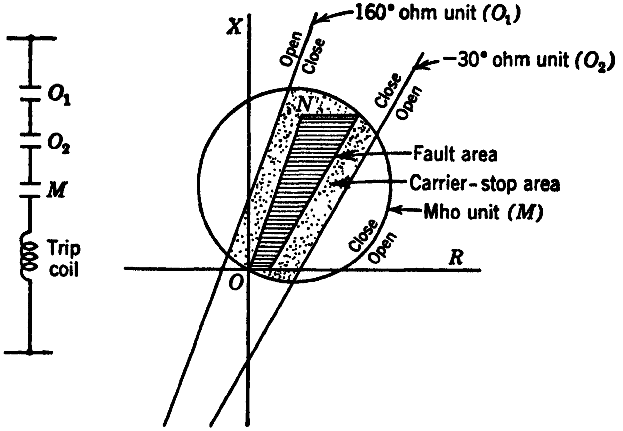


FIG. 22. The use of ohm relay units as "blinders" to narrow the angular range in which tripping can occur during swings.

The diameter of the mho circle, which is also very nearly the reach of the mho relay for faults, should not exceed this value if it is not to trip during swings. On the supposition that the mho relay is set to reach 1.10 times the length of the protected section, that length should not exceed $0.58Z/1.10 = 0.52Z$, or about half of *Z*. The corresponding limit for the impedance relay is about one-fourth of *Z*.

If the angular range covered by the mho relay is too wide, it may be narrowed to any desired extent by the use of additional relay elements, as shown in Fig. 22.[9] There the area of fault impedance is horizontally hatched. The impedance seen during metallic faults on the protected section lies on the line *ON*, and that seen during arcing faults lies to the right of *ON*. The tripping area, which is stippled, includes and surrounds the fault area and is bounded by the circular characteristic of a mho unit *M* and the linear characteristics of two "ohm" units, O_1 and O_2. The ohm units are similar to reactance units except that they respond to impedance at angles of +160° and −30° instead of

+90°. These angles are selected to make the characteristics of the ohm units parallel to the boundaries of the fault area, and the ohm settings are chosen to place the characteristics close, but not too close, to those boundaries. Ohm unit O_1 closes its contacts for impedances to the right of its characteristic line; O_2, for impedances to the left of its line; and mho unit M, for impedances inside its characteristic circle. Because the contacts of the three units are connected in series, tripping can occur only for impedances in the trip area. The setting of the mho unit controls the reach of the relay for faults. The settings of the ohm units control the angular range of tripping on swings. The ohm units have been appropriately called "blinders," as they permit the relay to "see" farther along the protected line MN than to either side.

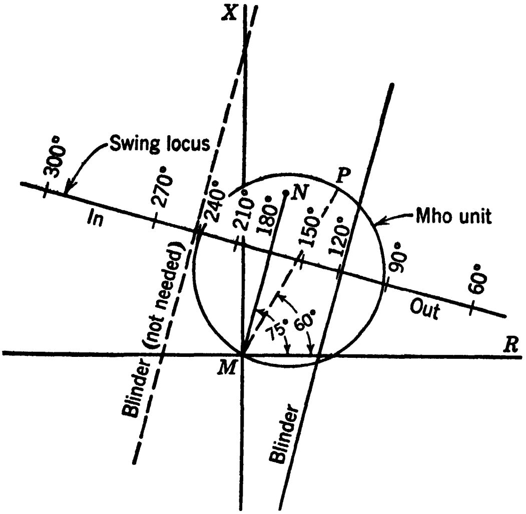


FIG. 23. Sometimes only one blinder is required. For example, to prevent tripping on swings up to ±120° on a line with 75° impedance angle, the 60° mho-unit circle and one blinder set at 120° suffice.

Carrier relays having the characteristic shown in Fig. 22 have been installed on a 270-mile 154-kv. line, a swing-impedance locus of which is shown in Fig. 20. On this line an impedance relay, set to reach the distant end of the circuit, would trip during swings in the range from about 50° to 310°, or 260° in width; the mho relay without blinders would trip in the range from 75° to 250°, or 175° in width; whereas with blinders the range is limited to that between 120° and 210°, or 90° in width. A back-up impedance relay would cover so great an angular range that it would trip at normal load. The blinders limit not only the width of the carrier trip area but also the width of the time-delay back-up trip area.

In some applications only one blinder is required instead of two. Thus, in Fig. 23 the line-impedance angle is 75°, but the mho-relay circle has its diameter *MP* at an impedance angle of 60°. Blinder characteristics are drawn intersecting the swing locus at 120° and at 240°; but, since the 240° blinder characteristic does not enter the mho circle, this blinder is superfluous. Only the 120° blinder is required to prevent tripping outside the range from 120° to 240°.[14] If the line were to be operated always with power flowing in, both blinders could be omitted.

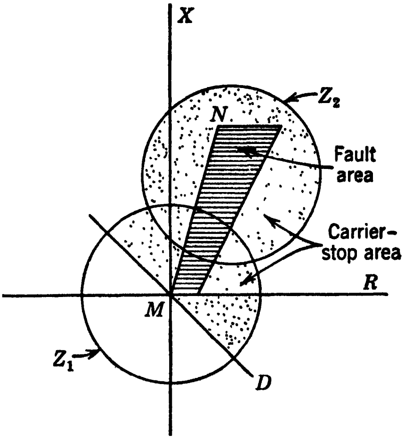


FIG. 24. Narrow trip area obtained by use of a second-zone circle Z_2 which does not include the origin *M*.

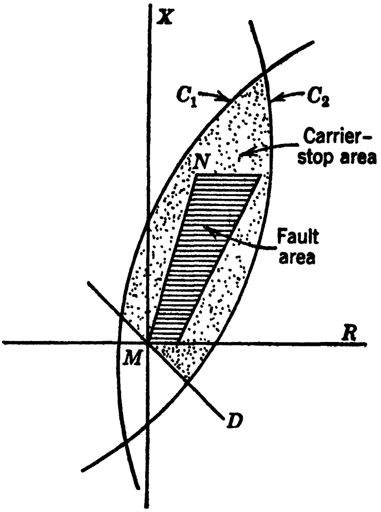


FIG. 25. Narrow trip area obtained by use of two circular characteristics, C_1 and C_2, of large diameter.

Instead of using "ohm" relays as blinders, one may narrow the width of the tripping area in other ways. Two methods which have been proposed[13] are shown in Figs. 24 and 25. The first method (Fig. 24) uses a second-zone relay element having a characteristic circle which does not include the origin. The diameter of such a circle—and consequently the angular range covered by it—is smaller than that of either an impedance element or a mho element of the same reach. The first-zone element is shown as an impedance element supervised by a directional element, though it could be a mho element. The second method (Fig. 25) utilizes a directional element and two elements having circular characteristics of large diameter. The latter elements perform the function of blinders, but, because their circles intersect, no other distance element is required to limit the reach on faults—at least not for use in a carrier-pilot scheme.

Even the relay scheme of Fig. 22, which will not trip during swings when no fault is present, may trip falsely during an external fault if there is at the same time a large angular displacement between the voltages at the two ends of the protected circuit. The false tripping is caused by the single-phase mho unit on an unfaulted phase-pair and may be avoided by supervising the mho units with a polyphase directional relay.[9]

Figure 17 (p. 186) illustrates the loci of impedances $\mathbf{Z}_{ac}$ and $\mathbf{Z}_{ba}$ seen during a fault by the relays on the unfaulted phases and affords a comparison of those impedances with the impedance $\mathbf{Z}_{cb}$ seen by the relay on the faulted phase and impedance $\mathbf{Z}_R$ seen by the relays on all phases when there is no fault. This figure shows that, although the fault might be beyond the balance point of the relay on the faulted phase-pair, it might appear to the relays on the unfaulted phase-pairs as an internal fault if the angle between the two generators should become great enough. The figure also shows that one effect of the fault is to bend the loci upward at the sides—an effect just opposite to that of shunt capacitance. This result can be explained qualitatively by noting that an unsymmetrical fault can be represented by an *inductive* shunt across the positive-sequence network at the fault location. Another effect, due to negative-sequence quantities, is the tilting of pole axis AB to the left for $\mathbf{Z}_{ac}$ and to the right for $\mathbf{Z}_{ba}$. The opposite tilts tend to put the operating point in the tripping area of one or the other of the two relays through a greater angular range than if there were no fault.

Out-of-step blocking. The methods described in the last section serve to prevent tripping on large swings but to permit tripping on out-of-step conditions. It is often desirable to prevent tripping even on out-of-step conditions; for, although it is good practice to separate machines or groups of machines which are out of step with one another, it is desirable to control the place where separation occurs. The point of separation should be chosen with a view to ensuring that each separated portion of the system has enough spinning reserve to supply its own load for at least the short time required to resynchronize the system or to put other generators on the line. Moreover, a point should be chosen where there are facilities for resynchronizing.

If no special provisions are made for out-of-step blocking, it may happen that circuit breakers are tripped at other points than the chosen one. This undesired tripping can be prevented by methods which will be described presently. Less frequently it may also happen that the chosen breaker is not tripped during out-of-step operation. In this event, special out-of-step tripping relays, similar in principle to out-of-step blocking relays, can be employed to ensure tripping.

Out-of-step blocking is nearly always used in conjunction with high-speed distance relays, sometimes without carrier current but more often with it. Out-of-step blocking rests on the principle that, although the vector impedance seen by the relays during out-of-step conditions may momentarily be identical with the impedance seen during a three-phase fault, there is this difference: Upon occurrence of a fault, the impedance changes *suddenly* from a normal-load value to a fault value, whereas during out-of-step conditions the change of impedance (which traverses a swing-impedance locus, discussed earlier in this chapter) is much more gradual. This principle is sometimes called the use of "rate of change of impedance." Whether or not tripping is permitted depends upon the time required for the impedance to change from one preselected value to another.

It has already been shown that the tripping characteristics of a distance relay can be portrayed by delineating a "trip area" in the complex impedance plane. For example, this area for an impedance relay is semicircular, bounded by the circular characteristic of an impedance element Z_2 and the straight-line characteristic of a directional element D, as shown in Fig. 26. Now suppose that the trip area is surrounded, and separated from the normal-load area, by a "buffer area," which, in Fig. 26, is cross-hatched. The outer boundary of the buffer area in this figure is the characteristic of another impedance element, Z_3, set for a higher impedance than element Z_2. In carrier-pilot relays the buffer area may be identical with the area of carrier transmission. Figure 26 could represent Type HZ carrier relays, in which carrier is started by the third-zone impedance element and is stopped by the combined action of the second-zone impedance element and the directional element. As a second example, the trip area of a mho relay is bounded by a circle through the origin, M_2 in Fig. 27, and a buffer area is bounded by this circle and the concentric larger circle MB of an offset mho relay.

The impedance seen by the relays cannot change from a normal-load value to a value in the trip area without passing across the buffer area. In event of a fault, the transition is made instantly; in event of out-of-step operation, more slowly. The elapsed time between the

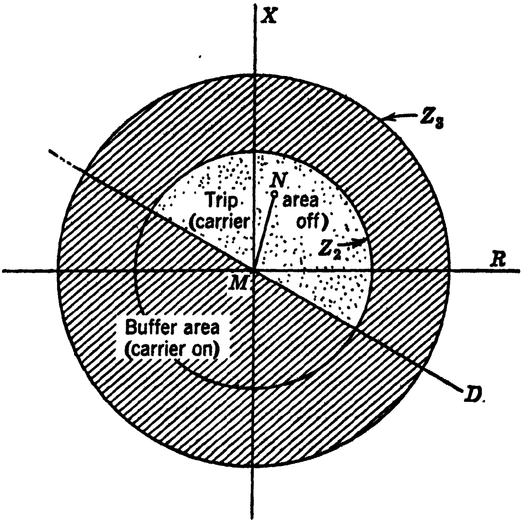


FIG. 26. Trip and buffer areas of impedance relay with out-of-step blocking.

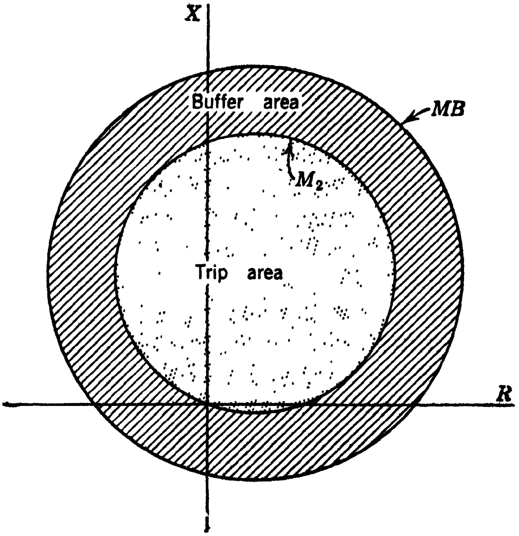


FIG. 27. Trip and buffer areas of mho relay with out-of-step blocking.

crossings of the inner and of the outer boundary of the buffer area serves to determine whether tripping shall be blocked.

When used with carrier-pilot relays, out-of-step blocking may be accomplished in at least two different ways: (1) by continuing the transmission of carrier signal, and (2) by opening the trip circuit. Without carrier, only the latter method is available. It is also the method now commonly used with carrier.

Type HZ carrier-pilot relays. The relay contact circuits required to accomplish out-of-step blocking in the Westinghouse Type HZ carrier-pilot relay scheme are shown, greatly simplified, in Fig. 28. Here D, Z_2, and Z_3 are the contacts of relay elements having the characteristics shown in Fig. 26, and X is an auxiliary relay having a pick-up time of 3 or 4 cycles. If contacts D, Z_2, and Z_3 close almost simultaneously, as they do when a fault occurs, the trip coil is energized before relay X has time to open the trip circuit. If, on the other hand, contacts Z_3 close 4 or more cycles before both D and Z_2 have closed, as would occur in swinging or out-of-step operation, relay X opens the trip circuit in time to prevent tripping, and holds it open until the swing impedance passes outside the Z_3 circle.

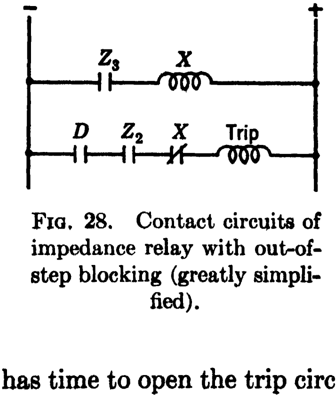


FIG. 28. Contact circuits of impedance relay with out-of-step blocking (greatly simplified).

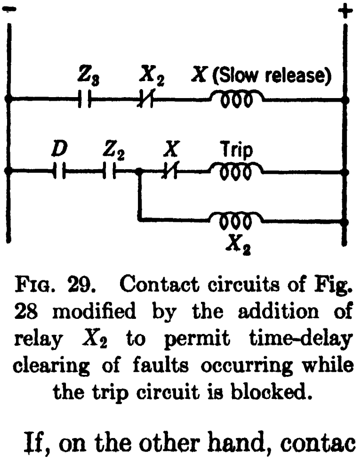


FIG. 29. Contact circuits of Fig. 28 modified by the addition of relay X_2 to permit time-delay clearing of faults occurring while the trip circuit is blocked.

The simplified blocking scheme of Fig. 28 has the shortcoming that a phase fault occurring during out-of-step conditions and during the part of the slip cycle when tripping is blocked would not be cleared because the blocking would remain in effect. Such an occurrence is possible, though not probable, and means should be provided for clearing the fault in a reasonable time. This may be done by making X a slow-release relay, having a pick-up time of 3 or 4 cycles, as before, and a drop-out time of about 30 cycles, and by adding another auxiliary relay, X_2, as shown in Fig. 29, to de-energize the coil of relay X

as soon as the impedance enters the trip area (that is, as soon as contacts D and Z_2 close). Relay X will not release until 30 cycles later, a time sufficient for the impedance to leave the tripping area unless a fault occurs in the protected zone, in which case tripping will take place upon expiration of the release time.

Blocking is not needed unless the impedance condition on the protected line appears like that of a three-phase fault. Therefore the circuits of Fig. 29 may be modified by putting the Z_3 contacts of all three phases in series to initiate blocking. Furthermore, back contacts of the three Z_3 elements may be placed in parallel with the X back contacts, in order to discontinue blocking just as soon as the impedance of one or more phases increases enough to allow the Z_3 impedance elements of such phases to reset. These changes are shown in Fig. 30. Then, if a line-to-line fault should occur during swinging and while blocking was in effect, it would be cleared as soon as the swing impedance passed outside the buffer zone and without awaiting expiration of the release time of relay X (as would be necessary for a three-phase fault). Ground relays (G in Fig. 30) need not be blocked; therefore a ground fault occurring during swinging can be cleared immediately.

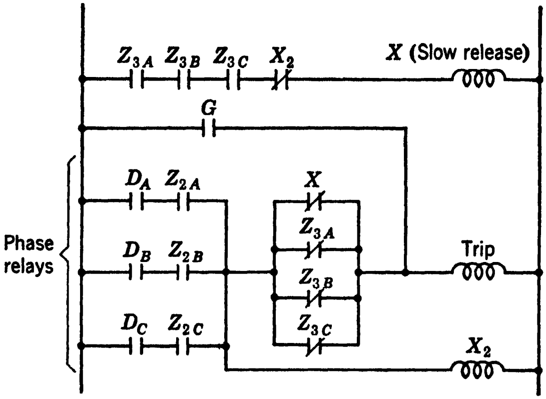


FIG. 30. Contact circuits of Fig. 29 modified for use on a three-phase circuit with phase and ground relays. The ground relay G is never blocked. The phase relays are blocked only during an actual or apparent three-phase fault and then only until expiration of the release time of relay X.

The general principles of Fig. 30 can be applied to impedance relays either with or without carrier current.

The contact circuits of Westinghouse Type HZ carrier-pilot relay scheme with out-of-step blocking are shown in reasonably complete form in Fig. 31. This figure should be compared with Fig. 33 of Chapter IX, where the out-of-step blocking is omitted and where only one of the three phase relays is shown. The parts added for out-of-step blocking in Fig. 31 are shown in heavy lines. These parts will be recognized as similar to those shown in Fig. 30, except for the following differences:

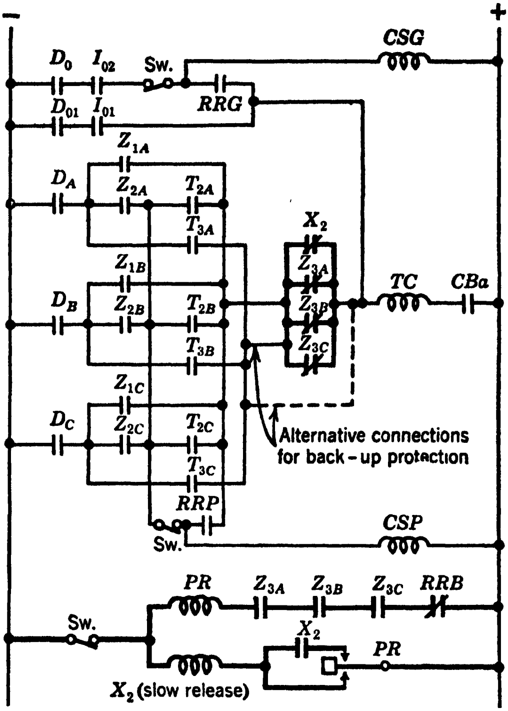


FIG. 31. Simplified schematic diagram of circuits of Westinghouse Type HZ carrier-pilot relay scheme with out-of-step blocking. Compare Fig. 33 of Chapter IX, which omits the blocking feature. The parts added to produce out-of-step blocking are shown in heavy lines.

PR Pendulum relay.
X_2 Slow-release auxiliary relay.

1. The group of contacts labelled "Phase relays" in Fig. 30 is replaced by a larger group of contacts, including those of the three impedance zones and of the timers.
2. Relay winding X_2 of Fig. 30 is replaced by relay winding *CSP*; and contacts X_2, by contacts *RRB* of the receiver relay. It will be

recalled that the receiver relay is released, thereby opening contacts *RRB*, if relays *CSP* are energized at *both* ends of the line by closing of the directional and second-zone contacts. Hence the two arrangements are nearly equivalent.

3. The slow relay X of Fig. 30 is actually two relays, *PR* and X_2, in Fig. 31. *PR* is a pendulum relay which, when energized, closes the lower contacts, thereby energizing X_2, which picks up after a few cycles delay. When *PR* is de-energized, its armature swings, alternately closing the upper and lower contacts and thereby energizing X_2 often enough to prevent it from releasing. After the amplitude of vibration of *PR* decreases sufficiently, the contacts are no longer made, X_2 is de-energized, and shortly thereafter it releases.

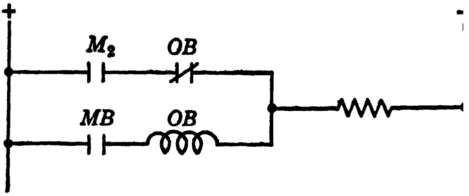


FIG. 32 Out-of-step blocking relay *OB* controlled by mho relays M_2 and *MB* (see Fig. 27).

If the third-zone impedance elements are connected as shown by the solid lines in Fig. 31, back-up protection of three-phase faults is prevented during an out-of-step condition. Back-up protection may be obtained under these circumstances by altering the connection to that shown by broken line.

Type GCY carrier-pilot relaying. Out-of-step blocking is provided in the Type GCY carrier-pilot relaying by means of an additional offset mho relay *MB* (Fig. 27) and the circuits shown in Fig. 32. If relay *MB* closes its contacts at least 0.05 sec. before M_2 does, out-of-step blocking relay *OB* is energized and remains so as long as *MB* is energized. If, on the other hand, *MB* and M_2 close their contacts simultaneously, as they will in event of a fault, the winding of relay *OB* is short-circuited and cannot be energized. When relay *OB* is energized, its contacts open the trip circuit. Usually only the trip paths of the first- and second-zone phase relays are blocked (as shown in Fig. 35 of Chapter IX); the third-zone and ground relays are not blocked.

Long lines. The methods of out-of-step blocking just discussed are not suitable for use on long lines if the trip and buffer areas are of the usual shape. The width of the buffer area is likely to be so great that normal-load impedances will lie in it and keep one set of fault detectors energized. Then, when a fault occurs, the relays will interpret it as a swing or out-of-step condition and will prevent immediate tripping of the circuit breakers. This difficulty can be avoided by making the buffer area narrower. Since the buffer area surrounds the trip area, narrowing the buffer area necessitates narrowing the trip area also. Both these areas can be made narrower by any of the means described in the preceding section of this chapter entitled "Prevention of tripping during swings," for example, by the use of "blinders."

If a long line interconnects two power systems, the place where the systems should be separated when they fall out of step is usually at either end of the long line itself. If so, there is no need for out-of-step blocking, and the methods described in the preceding section are suitable for blocking tripping during swings.

It is pertinent to remark here that phase-comparison carrier-pilot relays are inherently immune from tripping during swings or out-of-step operation and that they therefore require no complicated modifications for prevention of tripping from these causes.

Blocking of reclosure. If circuit breakers are arranged for high-speed reclosure (Chapter XI), tripping is sometimes permitted on out-of-step conditions, but reclosure should not be permitted after tripping from this cause. In other words, out-of-step blocking may be arranged to block reclosure but not to block tripping. In this case, a blocking relay is needed on only one pair of phases.

Out-of-step tripping relays. Infrequently cases arise where it is desired to trip a circuit breaker in order to separate two parts of a power system which are out of synchronism but where the regular protective relays do not trip because they are of types insensitive to out-of-step operation or because the out-of-step impedance locus does not enter their trip area—in other words, because the out-of-step condition looks like an external fault rather than an internal one. In such cases an additional relay can be provided to trip the breaker on out-of-step condition.

One method of distinguishing between an out-of-step condition and an external fault is by the rate of change of impedance. The characteristics of an out-of-step relay utilizing this principle consist of (1) an out-of-step trip area through which the out-of-step impedance locus is sure to pass, but which will not be entered during the largest swings from which the system can recover, and (2) a buffer area surrounding the trip area but not including any values of normal-load impedance.

Two possible characteristics are shown in Fig. 33. The one in part *a* of that figure is obtained by two ordinary nondirectional impedance elements Z_1 and Z_2 set for different values of impedance and is intended to trip for the out-of-step locus shown, which appears like a fault in the reverse direction. The characteristics in part *b* are obtained by modified impedance elements and are intended to trip for an out-of-step impedance locus which appears like a fault beyond protected section *MN*.

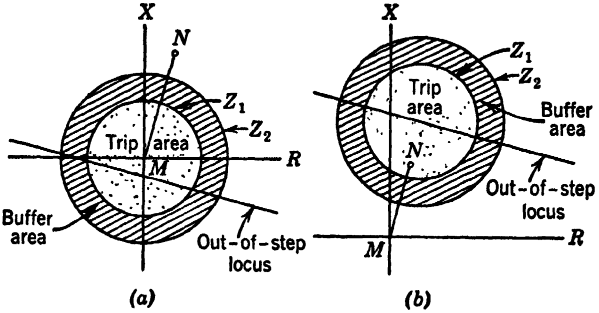


FIG. 33. Possible characteristics (in the impedance plane) of out-of-step tripping relays for out-of-step loci which do not cross the section *MN* which is to be tripped. (*a*) Locus crossing behind relay location *M*. (*b*) Locus beyond distant end *N*.

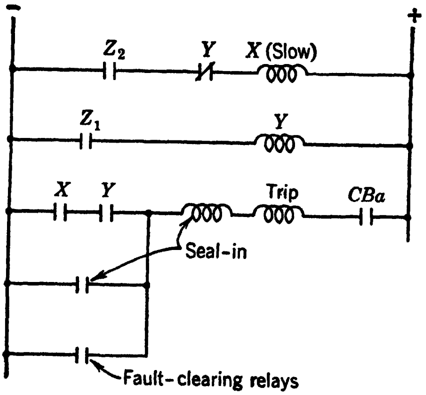


FIG. 34. Contact circuits of an out-of-step tripping relay.

Possible contact circuits are shown in Fig. 34. In the event of an external fault which lies within the tripping area, detectors Z_1 and Z_2 close their contacts simultaneously, energizing auxiliary relays *X* and *Y*, respectively. However, *X* is a slow relay, and *Y* opens its back contacts in series with the *X* coil before *X* can close its front contacts in the trip circuit. Therefore, tripping does not occur. If detectors Z_2 close their contacts several cycles before Z_1, then relay *X* closes its front contacts in the trip circuit. Later, when detectors Z_1 act, relay *Y* is energized and closes its front contacts, completing the trip circuit. Although relay X is simultaneously de-energized by the Y back contacts, its contacts remain closed long enough to energize the seal-in relay, which keeps the trip coil energized until the breaker opens.

Another method of detecting an out-of-step condition is to use two ohm elements O_1 and O_2 (Fig. 35) arranged to operate an auxiliary relay if the impedance crosses the two characteristic lines in succession in either direction. Advantages of this method are:

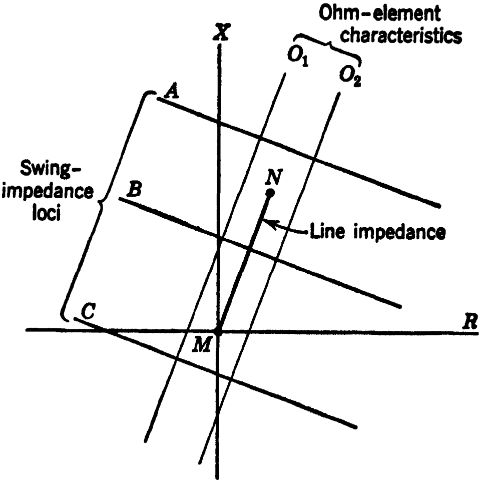


FIG. 35. Impedance characteristics of an out-of-step tripping relay having two ohm elements.

1. It operates on any swing-impedance locus (for example, A, B, or C in Fig. 35).
2. It can distinguish between fast and slow running of the local generators.

The out-of-step relay can be connected to sound an alarm or to trip a breaker either for separating the parts of the system that are out of step with each other or for dumping load.

A relay on one pair of phases suffices for detecting an out-of-step condition if faults are cleared rapidly.

Reverse back-up protection.[14, 18] On lines protected by distance relays with or without carrier, the customary way of providing back-up protection for adjacent sections of line is to set the third-zone distance element of each relay to reach beyond the end of the second section ahead of it. (Thus, in Fig. 36, relay *C* should reach beyond *F*.) On long lines, this method requires the third-zone element to have so high a setting that it may trip from heavy loads or small swings. A lower setting can often be used, and thus the likelihood of tripping on overloads or swings can be reduced, by connecting the third-zone element to trip for faults in the section *behind* it. Thus, in Fig. 36, time-delay back-up protection for line section *EF* is provided by the third-zone element of the relay at *D* tripping breaker *D*. The reach required of this element is only from *D* to a point beyond *F*, which is shorter by length *CD* than the reach required of a similar element

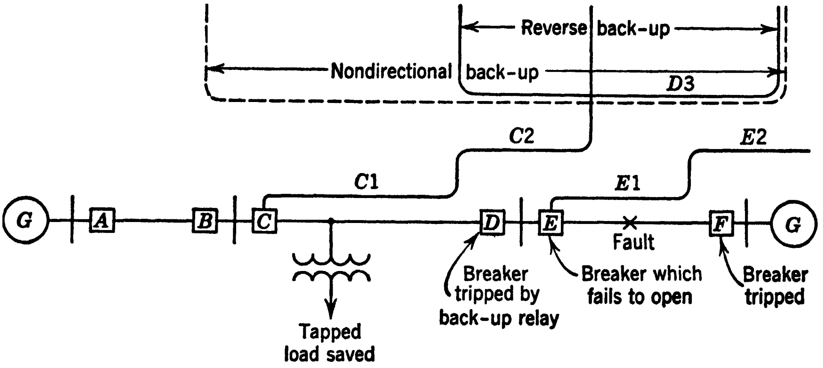


FIG. 36. Reverse back-up protection. Breaker *E*, which fails to open, is backed up by *D* instead of *C*, thus avoiding interruption of tapped load.

at *C* in order to protect section *EF*. The shorter the reach, the less is the likelihood of false tripping on swings or heavy loads.

Another advantage of reverse back-up protection over conventional back-up protection is the avoidance of interruption of tapped loads. For example, if breaker *E* should fail to open for a fault on section *EF*, breaker *C* would be tripped by the conventional scheme, interrupting the load tapped from line *CD*. If the reverse scheme were used, however, breaker *D* would be opened instead of *C*, and the tapped load would be saved. (Note, however, that, if the fault is near *E*, breaker *C* will be opened with second-zone time delay unless section *CD* has carrier arranged to block not only instantaneous tripping but also second-zone time-delay tripping in the event of an external fault.)

A disadvantage of reverse back-up protection is that failure of the d-c. tripping power or of the a-c. potential may cause breaker *D* to fail to open for the same reason that *E* fails.

In order to make a third-zone impedance element trip only for faults behind it, there must be additional directional contacts. In many locations, however, this impedance element may be made nondirectional without its overreaching in the forward direction (see broken curve in Fig. 36).[14] Since each element of a mho relay is inherently directional, the third-zone mho element can be connected oppositely from the first- and second-zone elements.[18] It is given an offset characteristic in order to provide good torque for nearby faults. Its zone extends forward a short distance and backward through an entire section (see Fig. 34 of Chapter IX and the solid curve $D3$ in Fig. 36).

Out-of-step protection of individual synchronous machines.[12] When a synchronous generator or motor pulls out of step with the rest of the synchronous machinery on a power system, damage may be done both to the machine itself and to the service rendered by the power system. Damage to the machine may consist of overheating of the damper winding or rotor core, or of mechanical damage, such as loosening of holding-down bolts or of coupling bolts or shaft breakage due to severe vibration, possibly aggravated by mechanical resonance. Damage to service is caused by reduction of voltage or fluctuation of voltage. Both forms of damage are minimized by disconnecting the machine after it pulls out of step or, preferably, even somewhat before it pulls out of step.

Before loss of synchronism. A synchronous generator or motor may pull out of step because of one or more of the following conditions: (1) load in excess of steady-state limit with normal excitation; (2) sudden great change of load; and (3) abnormally low field current or complete loss of field. A synchronous motor may pull out of step also because of (4) decrease in applied voltage.

Warnings of some of these conditions can be furnished by relays. The relays either may operate an alarm to invite manual correction of the condition or disconnection of the machine, or may automatically disconnect the machine before it loses synchronism.

Steady overload usually overheats the machine, and warning can be given by overcurrent relays or by watt relays. A sudden change of load causes loss of synchronism so rapidly, if at all, that a warning is of no value in preventing loss of synchronism. Undervoltage relays are usually provided on synchronous motors to disconnect the motor from the line. Such relays should have time-delay characteristics to prevent tripping on momentary voltage dips, such as those caused by short circuits, and therefore they are too slow to anticipate loss of synchronism.

Loss-of-field protection. Accidental loss of field is an important cause of synchronous machines losing synchronism. Loss of field may be caused by trouble in the field winding itself, in the field rheostat, or in the exciter; by a short circuit on the slip rings or wiring; or by unintentional tripping of the field circuit breaker.

On a certain large metropolitan system five serious machine-excitation failures occurred during 15 years, and, largely because of the disturbing effect of such failures on bus voltage, it was deemed desirable to provide loss-of-field protection to disconnect a generator from the bus before it should go out of step.[8]

The use of an *undercurrent relay* in the field circuit naturally suggests itself. Such a relay is not wholly satisfactory, however, because if it is set low enough so as not to operate at no-load excitation, it will fail to operate at values of excitation which are inadequate for maintaining stability at full load. Thus an undercurrent relay detects complete loss of field but does not provide positive indication of inadequate excitation for a given output. Furthermore, if time delay is provided to prevent tripping during transient conditions of low field current immediately after clearing of external faults on the armature circuit, the relay will not be fast enough to disconnect a machine with inadequate excitation before it pulls out of step.

A better method is to use a *polyphase reactive-current relay* in the armature circuit. When a generator loses field, it draws excitation from the bus, actuating the relay. The contacts of the reactive-current relay are connected in series with the contacts of an undervoltage relay to prevent disconnection of the generator unless the bus voltage decreases to a value below which continued operation would be inadvisable.

After loss of synchronism. Though the approach of loss of synchronism cannot always be determined with certainty, actual loss of synchronism can be identified after several cycles of slip. Loss of synchronism must be distinguished from faults and from swinging or hunting.

A condition which exists during out-of-step operation, and which has been used successfully in out-of-step relays, is repeated reversal of power, indicated by alternate closing of the forward and reverse contacts of a duodirectional watt relay. Power reversal may occur also upon the initiation and clearing of a fault, but is not repetitive unless multiple reclosure is used. Therefore a distinction is made by use of a notching, or counting, element, so that several cycles of power reversal are required to close the trip circuit. To prevent notching up by repeated short circuits, the notching element is arranged to reset if the sequence is not completed within a certain time interval. Repeated power reversal may occur also during hunting at light load. Tripping under such conditions is prevented by connecting the contacts of an overcurrent relay in series with those of the watt relay. If hunting or swinging occurs at heavy load, the power fluctuates but does not reverse.

The combination, just described, of a duodirectional element, overcurrent element, and notching element will detect loss of synchronism in all cases except when a machine pulls out of step because of complete loss of field. A cylindrical-rotor generator without field excitation may operate as an induction generator at 1 or 2% slip without reversal of power. Protection against out-of-step operation from this cause has already been discussed.

REFERENCES

1. M. Walter, "Ueber das Verhalten der Distanzrelais bei Pendelerscheinungen (On the Behavior of Distance Relays during Swings)," *Elektrotechnik und Maschinenbau* (Vienna), vol. 50, pp. 261–3, April 24, 1932.
2. Lloyd F. Hunt and A. A. Kroneberg, "Some Recent Relay Developments," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 530–5, April, 1934.
3. E. H. Bancker and E. M. Hunter, "Distance Relay Action during Oscillations," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 1073–80, July, 1934. Disc., vol. 53, pp. 1320–2, September, 1934; vol. 54, pp. 216–8, February, 1935.
4. H. D. Braley and J. L. Harvey, "Fault and Out-of-Step Protection of Lines," *A.I.E.E. Trans.*, vol. 54, pp. 189–200, February, 1935. Disc., vol. 55, pp. 197–9, February, 1936.
5. Leslie N. Crichton, "A System Out of Step and Its Relay Requirements," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 56, pp. 1261–7, October, 1937. Disc., vol. 57, pp. 284–6, May, 1938.
6. C. R. Mason, "Relay Operation during System Oscillations," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 56, pp. 823–32, July, 1937. Disc., vol. 56, pp. 1513–4, December, 1937; vol. 57, pp. 111–3, February, 1938.
7. H. R. Vaughan and E. C. Sawyer, "Out-of-Step Blocking and Selective Tripping with Impedance Relays," *A.I.E.E. Trans.*, vol. 58, pp. 637–45, December, 1939. Disc., pp. 645–6.
8. G. C. Crossman, H. F. Lindemuth, and R. L. Webb, "Loss-of-Field Protection for Generators," *A.I.E.E. Trans.*, vol. 61, pp. 261–6, May, 1942. Disc., pp. 462–3.
9. A. R. van C. Warrington, "Protective Relaying for Long Transmission Lines," *A.I.E.E. Trans.*, vol. 62, pp. 261–8, June, 1943. Disc., p. 427.
10. F. C. Poage, C. A. Streifus, D. M. MacGregor, and E. E. George, "Performance Requirements for Relays on Unusually Long Transmission Lines," *A.I.E.E. Trans.*, vol. 62, pp. 275–83, June, 1943. Disc., pp. 422–5.
11. C. W. Minard, R. B. Gow, W. A. Wolfe, and E. A. Swanson, "Staged Fault Tests of Relaying and Stability on Kansas-Nebraska 270-Mile 154-Kv. Interconnection," *A.I.E.E. Trans.*, vol. 62, pp. 358–67, 1943. Disc., pp. 425–6.
12. Relay Subcommittee of the A.I.E.E. Committee on Protective De-

VICES, "Interim Report on Application and Operation of Out-of-Step Protection," *A.I.E.E. Trans.*, vol. 62, pp. 567–73, September, 1943.

13. ERIK FLOOR, H. N. MULLER, JR., and S. L. GOLDSBOROUGH, "Transmission and Relaying Problems on the Fort Peck Project," *A.I.E.E. Trans.*, vol. 63, pp. 209–14, May, 1944. Disc., pp. 466–7.

14. R. E. CORDRAY and A. R. VAN C. WARRINGTON, "The Mho-Carrier Relaying Scheme," *A.I.E.E. Trans.*, vol. 63, pp. 228–35, May, 1944. Disc., pp. 434–6.

15. H. J. CARLIN and J. L. BLACKBURN, "A New Frequency Relay for Power-System Applications," *A.I.E.E. Trans.*, vol. 63, pp. 553–7, August, 1944. Disc., pp. 1421–2.

16. W. A. MORGAN, "New Distance Relays Know Faults from Swings," *Elec. Wld.*, vol. 124, no. 17, pp. 85–7, October 27, 1945.

17. EDITH CLARKE, "Impedances Seen by Relays during Power Swings with and without Faults," *A.I.E.E. Trans.*, vol. 64, pp. 372–84, 1945. Disc., pp. 471–2.

18. A. R. VAN C. WARRINGTON, "Application of the Ohm and Mho Principles to Protective Relays," *A.I.E.E. Trans.*, vol. 65, pp. 378–86, June, 1946. Disc., pp. 490–1.

19. LLOYD F. HUNT, "Slip Cycle Relays Automatically Separate Power Systems," *Elec. Wld.*, vol. 126, no. 11, p. 97, September 14, 1946.

20. B. V. HOARD and J. R. CURTIN, "Power System Development for Service to Hanford Plutonium Plant," *A.I.E.E. Trans.*, vol. 65, pp. 773–8, November, 1946.

21. R. RENCHON, "A General Cause of Inadvertent Operation of Interconnectors," *C.I.G.R.E.*, 1946, vol. 3, report 308, 9 pp.

22. ÅKE T. VRETHEM and GUNNAR JANCKE, "Selective Protective Relay Equipment for High-Voltage Systems with Long Overhead Transmission Lines," *C.I.G.R.E.*, 1946, vol. 3, report 327, 28 pp. Protection of 220-kv. network in Sweden.

23. W. A. MORGAN and BYRON EVANS, "Relaying Difficulties Disclosed by Staged-Fault Tests," *A.I.E.E. Trans.*, vol. 67, part I, pp. 73–82, 1948.

24. A. R. VAN C. WARRINGTON, "Graphical Method for Estimating the Performance of Distance Relays during Faults and Power Swings," *A.I.E.E. Trans.*, vol. 68, part I, pp. 608–20. Disc., pp. 620–1.

PROBLEMS ON CHAPTER X

1. Plot, in the complex admittance plane, the locus of the admittance "seen" by relays at $m = 0.25$, $m = 0.50$, and $m = 0.75$ in the two-machine system of Fig. 1 if $E_A = E_B$.

2. Plot, in the complex admittance plane, the locus of the admittance "seen" by relays at $m = 0.25$ in the two-machine system of Fig. 1 (*a*) for $E_A/E_B = 1.15$ and (*b*) for $E_A/E_B = 0.87$.

3. Plot, in the complex current plane, the locus of the vector current in the two-machine system of Fig. 1 with respect to the voltage at $m = 0.50$. Take $E_A = 1.15$, $E_B = 1.00$, and $\mathbf{Z} = 1\underline{/75^\circ}$ per unit.

4. Repeat Prob. 3 for $m = 0.75$.

5. Repeat Prob. 3 for $m = 0$.

6. Repeat Prob. 3 for the point of the system at which the apparent fault is located.

7. What would be the nature of the impedance locus of an electrically long line terminated in a short circuit as the length of the line is changed?

8. Plot the locus of the input impedance of a short-circuited line having the 60-cycle constants given below, as the length of the line varies from zero to 1,000 miles.

Series resistance = 0.252 ohm per mile
Series inductive reactance = 0.803 ohm per mile
Shunt conductance, negligible
Shunt capacitive susceptance = 5.22×10^{-6} mho per mile

Mark points 200 miles apart.

9. Compute and plot the near-end impedance circle for the 270-mile line of Example 4 if $E_r/E_s = 1.10$.

10. Compute and plot the far-end impedance circle for the 270-mile line of Example 4 if $E_r/E_s = 1.10$.

11. In Example 4, what is the near-end power if $E_r = E_s = 154$ kv. and if $\delta_{rs} = 50°$? If $\delta_{rs} = 230°$?

12. How far (in terms of the total impedance between the internal voltages of two generators at opposite ends of a transmission line) can a mho relay reach along the line without its being operated on power swings up to 150°?

13. If a mho relay is set to reach 100% of the impedance between internal voltages of two generators, how far apart can these voltages swing without actuating the relay?

14. Plot, in the admittance plane, the following loci pertaining to the system of Fig. 3: (*a*) the swing locus seen by relays at breaker 1 with $E_A = E_B$, marking thereon values of δ at 30° intervals; (*b*) the locus for short circuits on the protected line, marking thereon distances in per cent of Z at intervals of 25%; (*c*) the tripping characteristics of a three-zone directional impedance relay, with directional element having maximum torque at 45° lag and with distance elements set at 0.8, 1.6, and 2.4 times the length of the protected section.

15. Add to the plot of the preceding problem the tripping characteristics of a reactance relay (consisting of first-zone and second-zone reactance elements and third-zone starting element with maximum torque at 60° lag) set for the distances mentioned.

16. Work Example 3, using symmetrical components instead of two-phase coordinates.

17. Work Example 3 for a two-line-to-ground fault instead of a line-to-line fault. Which type of fault subjects the phase relays of the unfaulted phases to the greater danger of false operation?

CHAPTER XI

RAPID RECLOSING

The great majority of faults on overhead transmission lines are transitory in nature. They disappear if the line is de-energized for a short while in order to permit the arc to become extinguished. After the arc has become sufficiently deionized, the line may be re-energized and put back into use. Lightning is the commonest cause of faults on overhead lines, and most faults caused by lightning are transitory. In addition, some faults due to other causes, such as swinging wires and temporary contacts with foreign objects, are transitory. On the other hand, a few faults on overhead lines (for example, those caused by broken wires or poles) and all faults on underground cables are permanent. Such faults must be located and repaired before the line can be successfully re-energized.

At first, lines were re-energized solely by manual reclosing of the circuit breakers. Beginning about 1922, automatic reclosure of circuit breakers was introduced in order to improve service through shortening the period of interruption. Reclosing relays were employed which automatically reclosed the breaker once ("single-shot" reclosing), twice, or even thrice in succession if it was tripped that many times. If an additional tripout occurred, however, the breaker remained open until it was closed manually. Each reclosure was made after a longer delay than the preceding one in the series. The usual delay times were 15 sec. for the first reclosure, 30 sec. for the second, and 45 sec. for the third. After a successful reclosure the relay reset itself in readiness for a new series. Operating experience showed that, in from 70 to 90% of the reclosing operations, the first reclosure was successful; in about half the remainder, the second or third reclosures were successful; and in the other half, lockout occurred.*

*For example, Logan[4] reports the following classification of 1,010 tripouts of reclosing circuit breakers occurring in the year 1933 on lines of voltages from 4 to 60 kv.:

In 896 cases (88.7%), the first reclosure was successful.
In 46 cases (4.5%), the second reclosure was successful.
In 13 cases (1.3%), the third reclosure was successful.
In 55 cases (5.5%), lockout occurred.
In 16 cases (1.6%), the breaker failed to reclose.

Later, in order to prevent loss of induction-motor load, the delay in the first reclosure was reduced to a fraction of a second in many installations. The percentage of successful reclosures was not appreciably reduced by the use of "immediate initial reclosure." To prevent loss of motor load, however, it was necessary to equip motor starters with time-delay, instead of instantaneous, undervoltage protection.

Automatic reclosing was first applied to stub feeders. Its use was later extended to lines fed from both ends. In the latter application it was necessary to make an automatic check on synchronism before reclosing. However, the reclosure was not made for the purpose of maintaining synchronism, but only to restore voltage to tapped loads.

High-speed reclosure of circuit breakers for the purpose of increasing the transient stability limit of a line connecting two groups of generators was explored by Griscom and Torok[2] in 1933 and was first put into practice in 1936 on a 132-kv. line of the American Gas and Electric Company.[10] Five years later the transmission system of that company had 33 high-speed reclosing breakers protecting 714 miles of 132-kv. line and 126 miles of 66-kv. line. During these 5 years there were 72 reclosing operations, of which 65 operations (about 90%) were successful.[14] Four years still later the same system had 91 high-speed reclosing breakers protecting 1,634 miles of line. During the 9 lightning years from May, 1936, to November, 1944, there were 635 cases of flashover causing breakers to open. In these 635 cases there were 570 successful reclosures (about 90%) and 65 unsuccessful reclosures.[35]

High-speed reclosure for improving stability is a step in advance of high-speed clearing of faults. Its effect on raising stability limits is especially marked when applied to single-circuit ties between systems; for without reclosure the power limit of a single-circuit tie is zero, whereas with reclosure the power limit may be considerable. While the line is open to permit deionization of the arc, the generators at the two ends of the line drift apart in phase. The breakers must be reclosed before the generators drift too far apart if synchronism is not to be lost. On double-circuit ties subjected to single-circuit faults, the connection through the sound circuit prevents the generators from drifting apart so fast, and the increase in power limit due to reclosing the faulted circuit is moderate but, nevertheless, is sometimes important. A further advantage of high-speed reclosing on double-circuit lines arises from the possibility of faults involving both circuits simultaneously. In such an event, the rapid reclosing of even one of the two circuits enables a considerable amount of power to be carried with stability.

Even though a line is reclosed when the generators are out of step or when they have such a large angular displacement that synchronism is temporarily lost after reclosure, it is possible that synchronism may be soon regained. This possibility is an additional reason for favoring rapid reclosing.

Reclosing used for improving stability is of the "single-shot" variety.

Factors affecting the feasibility of high-speed reclosing. The feasibility of rapid reclosure of breakers for maintaining stability and the gain in power limit produced thereby depend upon the following factors:

1. The maximum time available for opening and reclosing the circuit breakers without loss of synchronism. This is a function of the transmitted power and can be calculated by methods which are similar to those already considered in previous chapters. Such calculations will be considered more fully in a later part of this chapter.
2. The time required to deionize the arc at the fault, so that it will not restrike when the breakers are reclosed. This time has been found from tests conducted in high-voltage laboratories and from field experience with reclosing of breakers.
3. The least time in which circuit breakers can be opened and reclosed, as determined by mechanical and electrical limitations of the breakers themselves. This is a matter of the design of the circuit breakers and of their operating mechanisms.
4. The probability and duration of multiple, or repetitive, lightning strokes.
5. The probability of occurrence of permanent faults.

Note that there is a conflict between the first two items. The faster the breakers are reclosed, the greater the power that can be transmitted without loss of synchronism, provided that the arc does not restrike, but also the greater is the likelihood of the arc restriking. An unsuccessful reclosure is more detrimental to stability than no reclosure would be. Therefore the time during which the line is de-energized should not be reduced below that which suffices to keep arcs from hardly ever restriking. There is no objection, however, to reduction of the reclosing time obtained by speeding up the clearing of faults. Indeed, the increase in power limit due to reclosing is much greater with very rapid fault clearing than with slower fault clearing.

For best results, the breakers at both ends of the faulted line should open simultaneously and close simultaneously. Any time during which one breaker is open and the other closed is wasted both as regards deionization of the arc and as regards the transfer of synchronizing power over the line. Simultaneous high-speed relaying is therefore necessary. It is obtained, if possible, by setting distance relays to cover the entire length of the line; otherwise, by pilot-wire or carrier-current relaying.

Stability analyses. The effect of rapid reclosing on the stability of a two-machine system can be visualized most readily through the use of the equal-area criterion. First, power-angle curves must be

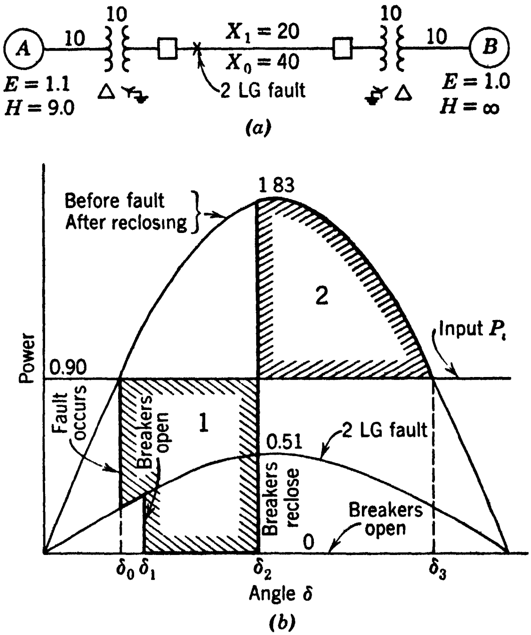


FIG. 1. Application of the equal-area criterion for stability to the reclosing of a single-circuit tie between systems A and B. For stability, area 2 should exceed area 1.

drawn for the several pertinent conditions: (1) before occurrence of the fault, (2) during the existence of the fault, (3) with the fault cleared, and (4) with the faulted line reclosed. The last condition, however, is the same as the first one.

Figure 1 shows such power-angle curves for a simple two-machine system consisting of a *single-circuit transmission line* connecting two groups of generators, A and B. The curve for normal conditions, of course, has the greatest height; that for the faulted condition is low (a two-line-to-ground fault is assumed; for a three-phase fault, the amplitude would be zero); and that for the breakers open has zero height. The height of the horizontal line labelled "Input" represents the electric power transmitted before the fault and also the mechanical power, which is assumed to be constant throughout the disturbance. The initial angular separation of machines A and B is δ_0, the clearing angle is δ_1, the reclosing angle is δ_2, and the angle of maximum swing without loss of synchronism is δ_3. For stability, area 2 must exceed area 1. Without reclosure, synchronism would be lost regardless of the amount of power transmitted. Hence the stability limit without reclosure is zero. With rapid enough clearing and reclosure, however,

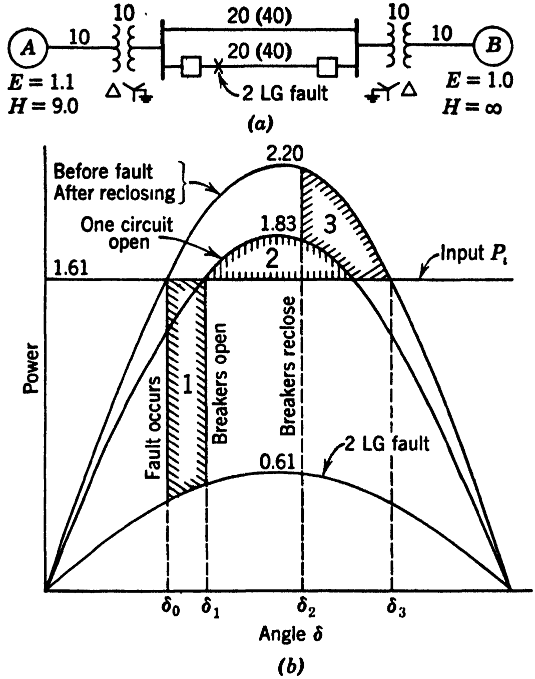


FIG. 2. Application of the equal-area criterion for stability to the reclosing of one circuit of a double-circuit tie between systems A and B. For stability, the sum of areas 2 and 3 should exceed area 1. Area 3 represents the gain in stability due to reclosing.

the stability limit can be made to approach the amplitude of the normal power-angle curve.

Figure 2 shows power-angle curves and the equal-area criterion for stability of a system consisting of two groups of generators connected through a *double-circuit line.* When one circuit has been opened to clear the fault, the power-angle curve is almost as high as the curve for normal conditions. For stability, the sum of areas 2 and 3 must exceed area 1. Area 3 represents the contribution of reclosure to stability.

Though Figs. 1 and 2 aid one in understanding the effect of reclosure upon stability, they are of little help in numerical calculation of stability limit because the switching angles δ_1 and δ_2 are unknown. Usually the switching times (that is, the clearing time and the reclosing time) are known or assumed, for they depend upon the speeds of relays and circuit breakers. In order to find the switching angles corresponding to these given switching times, a value of power must be assumed, and a swing curve must be computed either graphically or point by point. After the last switching angle δ_2 has been thus found, the equal-area criterion can be used to determine whether or not the system is stable. It is almost as easy, however, to determine this by continuing the computation of the swing curve to either the maximum angle of swing or the critical angle δ_3, whichever is reached first. If the maximum angle is reached first, the system is stable; if the critical angle is reached first, the system is unstable. If the assumed value of power is the stability limit, the angular velocity becomes zero at the critical angle δ_3, and the net area is zero. If the assumed value of power is not the power limit, and if the latter must be found, then the estimate should be revised and the calculation repeated until the power limit is found with the desired accuracy. When the assumed value of power is changed, the switching angles change also; therefore the equal-area criterion cannot be used correctly with the old angles, but, instead, a new swing curve must be computed in order to find new values of these angles. The method of Byrd and Pritchard (Ref. 3, Chapter V, Vol. I) is not applicable to reclosing problems or to any case where there is more than one instant of switching after occurrence of the fault.

EXAMPLE 1

Find the transient stability limit of the two-machine single-circuit power system of Fig. 1*a* if a two-line-to-ground fault at the sending end of the high-voltage transmission line is cleared in 0.15 sec. and the circuit breakers reclose 0.20 sec. later.

In Fig. 1*a*, the reactances are given in per cent; *E* and *H*, in per unit. The zero-sequence reactance of the line is twice as great as the positive-sequence reactance. The frequency is 60 c.p.s. Resistance and capacitance are to be neglected.

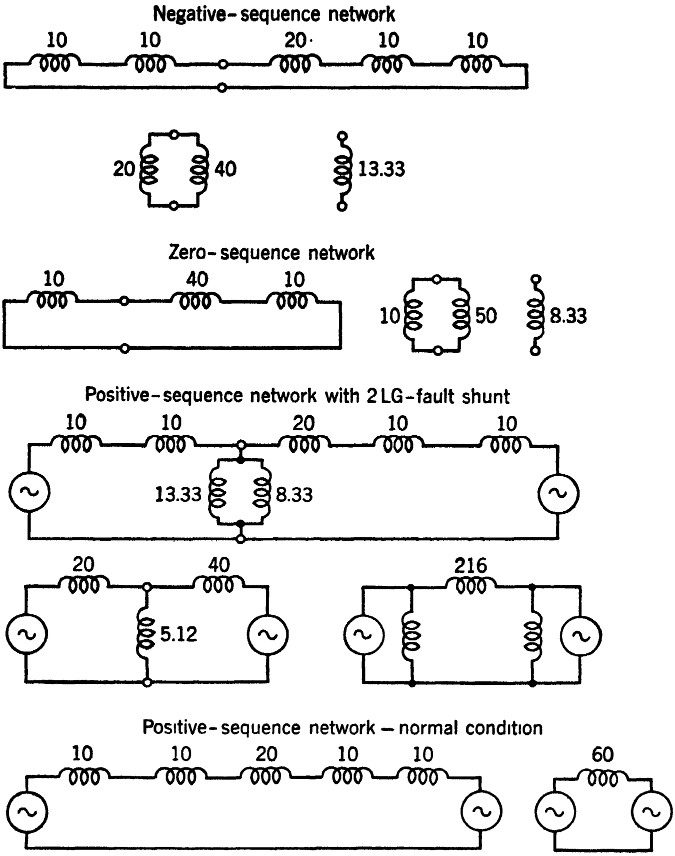

Negative-sequence network
10
10
20
10
10
20
40
13.33
Zero-sequence network
10
40
10
10
50
8.33
Positive-sequence network with 2LG-fault shunt
10
10
20
10
10
13.33
8.33
20
40
5.12
216
Positive-sequence network – normal condition
10
10
20
10
10
60

FIG. 3. Network reduction for Example 1.

Solution. The network reduction is shown in Fig. 3. The transfer reactances and the amplitudes of the power-angle curves are listed in Table 1 for the various conditions of the circuit. The amplitude of each power-angle curve is given by the equation

$$P_m = \frac{E_A E_B}{X_{AB}} = \frac{1.1 \times 1.0}{X_{AB}} = \frac{1.1}{X_{AB}}$$

The power-angle curves are plotted in Fig. 1*b*.

A value of power P_i is assumed, and a swing curve is calculated point by point up to the time of reclosure in order to find the switching angles. From the angles so found and the amplitudes of the power-angle curves, the net area (area 2 — area 1, Fig. 1) is calculated. A positive value of area shows

TABLE 1

REACTANCES AND AMPLITUDES OF POWER-ANGLE CURVES (EXAMPLE 1)

Condition	Reactance (per unit)	Amplitude (per unit)
Before fault	0.60	1.83
2LG fault on	2 16	0.51
Line open	∞	0
Line reclosed	0.60	1.83

that the system is stable; negative, unstable. If the assumed power is the stability limit, the area is zero. Several trials are usually necessary to find the power limit. In order to save space, however, only the final, successful trial is given here.

In the point-by-point calculation, Δt will be taken as 0.05 sec. The following constants are needed:

$$M = \frac{GH}{180f} = \frac{1 \times 9}{180 \times 60} = \frac{1}{1,200}$$

$$\frac{(\Delta t)^2}{M} = \frac{(1/20)^2}{1/1,200} = \frac{1,200}{400} = 3.0$$

The point-by-point computation is given in Table 2. In this table, the switching angles are as follows:

Fault occurs at $t = 0$, $\delta = \delta_0 = 29.4°$
Breakers open at $t = 0.15$ sec., $\delta = \delta_1 = 38.1°$
Breakers reclose at $t = 0.35$ sec., $\delta = \delta_2 = 82.3°$

The maximum angle for stable operation is $\delta_3 = 180° - \delta_0 = 180° - 29.4° = 150.6°$. This relation holds because at both angles, δ_0 and δ_3, the operating point is on the same sinusoidal power-angle curve at its intersections with the horizontal line representing the input power P_i. Vertical lines are drawn in Fig. 1*b* at the four angles, δ_0, δ_1, δ_2, and δ_3.

The net area will be computed as the irregular area below the heavy line in Fig. 1*b* less the area of the rectangle below the "Input" line between angles δ_0 and δ_3. The area below the heavy line is

$$\begin{aligned}
\int_{\delta_0}^{\delta_3} P_u \, d\delta &= \int_{\delta_0}^{\delta_3} P_m \sin \delta \, d\delta \\
&= 0.51 \int_{\delta_0}^{\delta_1} \sin \delta \, d\delta + 0 \int_{\delta_1}^{\delta_2} \sin \delta \, d\delta + 1.83 \int_{\delta_2}^{\delta_3} \sin \delta \, d\delta \\
&= 0.51(\cos \delta_0 - \cos \delta_1) + 1.83(\cos \delta_2 - \cos \delta_3) \\
&= 0.51(\cos 29.4° - \cos 38.1°) + 1.83(\cos 82.3° - \cos 150.6°) \\
&= 0.51(0.871 - 0.787) + 1.83(0.134 + 0.871) \\
&= 0.51 \times 0.084 + 1.83 \times 1.005 = 0.04 + 1.84 = 1.88
\end{aligned}$$

TABLE 2

Point-by-Point Computation of Swing Curve

(Example 1)

t (sec.)	sin δ	P_m	$P_u = P_m \sin\delta$	P_a	$3P_a$ (deg.)	$\Delta\delta$ (deg.)	δ (deg.)
0−	0.491	1.83	0.90	0			
0+	"	0.51	0.25	0.65			
0 avg.	....	....	....	0.325	1.0		29.4
						1.0	
0.05	0.506	"	0.26	0.64	1.9		30.4
						2.9	
0.10	0.549	"	0.28	0.62	1.9		33.3
						4.8	
0.15−	0.617	"	0.31	....	...		38.1
0.15+	.. ..	0	0				
0.15 avg.	.....	....	0.16	0.74	2.2		
						7.0	
0.20	.....	"	0	0.90	2.7		45.1
						9.7	
0.25	.....	"	"	"	"		54.8
						12.4	
0.30	.....	"	"	"	"		67.2
						15.1	
0.35−	.....	....	....	....	...		82.3

The rectangular area, expressed in the same units (radians for δ), is

$$\frac{150.6^\circ - 29.4^\circ}{57.3^\circ} \times 0.90 = \frac{121.2^\circ}{57.3^\circ} \times 0.90 = 1.90$$

The two areas, 1.88 and 1.90, are almost equal. Therefore 0.90 is very nearly the correct value of stability limit.

Example 2

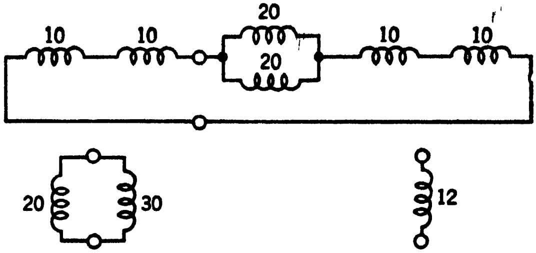
Find the power limit of the two-machine double-circuit power system of Fig. 2*a* for a two-line-to-ground fault at the sending end of one circuit, cleared in 0.15 sec., (*a*) with no reclosure and (*b*) with reclosure 0.20 sec. after clearing.

Solution. The network reduction is shown in Fig. 4. The transfer reactances and the amplitudes of the power-angle curves are listed in Table 3. The power-angle curves are plotted in Fig. 2*b*.

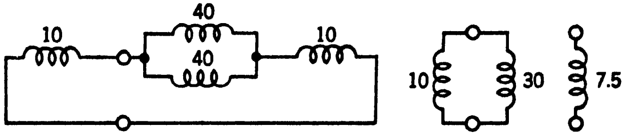
(*a*) For the case of no reclosure, the method of Byrd and Pritchard (Chapter V, Vol. I) can be used. A curve of stability limit versus clearing time is plotted, and the required value of stability limit is read for a clearing time of 0.15 sec.

$$r_1 = \frac{0.50}{1.80} = 0.278; \qquad r_2 = \frac{0.50}{0.60} = 0.833$$

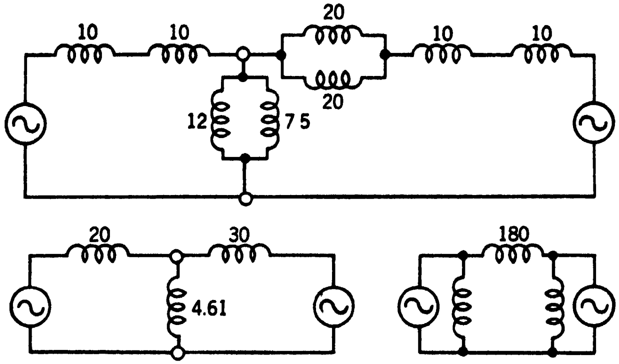
(a) Negative-sequence network



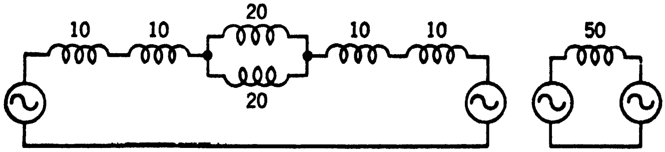
(b) Zero-sequence network



(c) Positive-sequence network with 2LG-fault shunt



(d) Positive-sequence network – normal condition



(e) Positive-sequence network – one line open

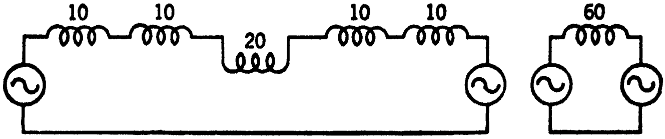


Fig. 4. Network reduction for Example 2.

TABLE 3

Reactances and Amplitudes of Power-Angle Curves (Example 2)

Condition	Reactance (per unit)	Amplitude (per unit)
Before fault	0.50	2.20
2LG fault on	1.80	0.61
One line open	0.60	1 83
Line reclosed	0 50	2.20

The following values of τ_c are read from the curves (pp. 174–5, Vol. I):

$\sin \delta_0$	0.60	0.65	0.70	0.75
τ_c	0.85	0.65	0 47	0.27
$t_c = 0.28\tau_c$	0.24	0.18	0.13	0 08
$P_i = 2.20 \sin \delta_0$	1 32	1.43	1 54	1.65

The values of t_c and P_i were computed as indicated. From a curve of P_i versus t_c, the value $P_i = 1.50$ per unit is read at $t_c = 0.15$ sec. Hence the stability limit without reclosure is 1.50 per unit.

TABLE 4

Point-by-Point Computation of Swing Curve (Example 2, Part *b*)

t (sec.)	$\sin \delta$	P_m	$P_u = P_m \sin \delta$	P_a	$3P_a$ (deg.)	$\Delta\delta$ (deg.)	δ (deg.)
0−	0.726	2 20	1 60	0			
0+	"	0.61	0.44	1.16			
0 avg.	.....	....	....	0 58	1.7		46.6
						1.7	
0.05	0.747	"	0.46	1.14	3.4		48.3
						5.1	
0.10	0.803	"	0.49	1.11	3.3		53.4
						8.4	
0.15−	0.881	"	0.54	......	.....		61.8
0.15+	"	1.83	1.61				
0.15 avg.	.....	....	1.08	0.52	1.6		
						10.0	
0.20	0.950	"	1.74	−0.14	−0.4		71.8
						9.6	
0.25	0.989	"	1.81	−0 21	−0.6		81.4
						9.0	
0.30	1.000	"	1.83	−0.23	−0.7		90.4
						8.3	
0.35−	.....	....	....	......	.....		98.7

(*b*) For the case of reclosure, a value of power is assumed; then a swing curve is computed up to 0.35 sec., and the equal-area criterion is applied, as in Example 1. For a power of 1.60 per unit, the swing-curve computation is given in Table 4.

The computation of area is as follows:

Area under power-angle curves is

$$\begin{aligned}&0.61\,(\cos 46.6^\circ - \cos 61.8^\circ) + 1.83\,(\cos 61.8^\circ - \cos 98.7^\circ)\\ &\qquad + 2.20\,(\cos 98.7^\circ - \cos 133.4^\circ)\\ &= 0.61(0.687 - 0.473) + 1.83(0.473 + 0.151) + 2.20(-0.151 + 0.687)\\ &= 0.61 \times 0.214 + 1.83 \times 0.624 + 2.20 \times 0.536\\ &= 0.130 + 1.141 + 1.179 = 2.450\end{aligned}$$

Rectangular area is

$$\frac{133.4^\circ - 46.6^\circ}{57.3^\circ} \times 1.60 = \frac{86.8^\circ}{57.3^\circ} \times 1.60 = 2.424$$

Net area is $2.450 - 2.424 = 0.026$.

A similar computation for $P_i = 1.70$ gives a net area of -0.187. By interpolation for zero area, $P_i = 1.61$. This is the stability limit with reclosure.

The results of Examples 1 and 2 are summarized in Table 5.

TABLE 5

POWER LIMITS WITH AND WITHOUT RAPID RECLOSURE, SINGLE-CIRCUIT AND DOUBLE-CIRCUIT LINES

(EXAMPLES 1 AND 2)

Line	Power Limit (per unit)		Increase Due to Reclosure
	Without Reclosure	*With Reclosure*	
Single-circuit	0	0.90	0.90
Double-circuit	1.50	1.61	0.11

Permanent faults. A small percentage of the faults on overhead lines are permanent—for example, those due to breakage of conductors or poles by airplanes, floods, earthquakes, or bombs. Rapid reclosure on a permanent fault is more detrimental to stability than no reclosure or long-delayed reclosure. Therefore, if the utmost reliability is desired, multiple circuits on separate routes are required, and high-speed reclosure should not be employed unless stability studies show that the system is stable even in the event of a permanent fault causing two successive openings of the line. If, however, infrequent loss of synchronism can be tolerated, the employment of rapid reclosing of multiple circuits raises the transient stability limit for the great majority of faults, which are transitory. The decision on whether to use rapid reclosure on multiple circuits should depend upon the expectancy of unsuccessful reclosure due to permanent faults, multiple lightning strokes, or other causes, and on the stability limits for the three conditions: (1) successful reclosure, (2) no reclosure, and (3) unsuccessful reclosure.

Obviously, reclosure should not be employed on cables, for nearly all cable faults are permanent. Likewise, reclosure is seldom, if ever, used in the event of bus faults because such faults are likely to be caused by damaged apparatus or by operating errors and are likely to require repairs or manual switching to clear them.

On a single overhead line, there is much more to be gained than lost by rapid reclosure. The transient stability limit is zero either with no reclosure or with unsuccessful reclosure. The only disadvantages of an unsuccessful reclosure over no reclosure are the presence of two successive voltage dips, increased duty on the circuit breaker, and the possibility of greater damage at the fault location. These slight disadvantages are more than offset by the high probability of successful reclosure. A single-circuit tie cannot provide the utmost reliability, but its reliability is immensely increased by the provision of rapid-reclosing breakers. The same is true to a lesser degree of double-circuit lines on the same towers, for there is considerable probability of simultaneous faults on both circuits.

Single-pole switching. In the foregoing discussion of rapid reclosing, it has been tacitly assumed that the three poles of a circuit breaker open together and reclose together, regardless of the type of fault, because that is the usual manner of breaker operation. If that kind of switching (*three-pole*, or *group*, operation) is applied to a single-circuit tie between two groups of generators, much of the change of kinetic energy of the generators occurs during the period when the breakers are open, because no synchronizing power can flow during this period. The amplitude of the power-angle curve for this condition is zero. If, on the other hand, only those breaker poles are tripped that are on the faulted phases, some power can still be transmitted. This mode of operation is called *single-pole*, or *selective-pole*, switching.

If single-pole switching is employed, only one pole of each breaker is tripped and reclosed in event of a line-to-ground fault. While one conductor is open, the circuit can carry a substantial amount of power on the two sound conductors and ground. In some installations, all three poles are opened on any other type of fault than one-line-to-ground. They may be automatically reclosed or not, as desired. In other installations, selective-pole switching is used not only for line-to-ground faults but also for line-to-line and two-line-to-ground faults. There one pole of each breaker is opened and reclosed for a line-to-line fault, and two poles for a two-line-to-ground fault. While two conductors are open, some power is carried on the remaining conductor with ground return, though less than if only one conductor were open. In event of a three-phase fault, of course, all three poles must be tripped, and they may be either reclosed or not, as desired.

Even though only the faulted phases are tripped the first time, all three poles should be opened and locked out after an unsuccessful reclosure in order to avoid sustained inductive interference with telephone circuits, which would be caused by zero-sequence currents set up in the power system by the unsymmetrical open circuit.

Through the use of single-pole tripping and reclosing, the stability limit of a single tie line can be raised above the limit obtainable with three-pole tripping and reclosing at the same speed. (Or, alternatively, for a given stability limit, slower switching can be used with single-pole switching than with three-pole.) The increase in stability limit is great for a line-to-ground or line-to-line fault, considerable for a two-line-to-ground fault, and nothing for a three-phase fault. On a double-circuit tie, the increases obtainable through single-pole switching are not so great as on a single-circuit tie. In appraising these results, it should be kept in mind that about 80% of all faults on overhead transmission lines are of the one-line-to-ground type† and that new lines can be designed so as to ensure that a still higher proportion of faults will be of this type.

Single-pole switching has some additional advantages which favor its use even in cases where three-pole switching suffices to maintain system stability. Single-pole switching decreases the amplitude of swing and the consequent voltage dip during the swing. It also reduces the great mechanical shock to the generator and its coupling at the instant of reclosing.[27, 36] (Compare lengths *AB* and *CD* in Fig. 6, p. 237, showing the sudden changes in power output at this instant for three-pole and single-pole reclosing, respectively.)‡

---

†Some representative data are the following:

(1) On the 60-kv. transmission system of the Kansas Gas and Electric Company, out of 451 tripouts of circuit breakers equipped with distance ground relays, 378 (83.8%) were caused by one-line-to-ground faults (Ref. E13 of Chapter IX).

(2) On the solidly grounded 140-kv. system of the Consumers Power Company, including nearly 1,000 miles of line, 256 line faults in the years 1941 to 1945 were analyzed from oscillograms; of these, 78% started between one line and ground, but 10% of the total number changed to multiphase faults before they were cleared (Ref. K1 of Chapter IX).

(3) Out of 72 operations of rapid-reclosing circuit breakers on 714 miles of 132-kv. line and 126 miles of 66-kv. line on the system of the American Gas and Electric Company in the 5-year period 1936 to 1940, 58 operations (80.6%) were caused by line-to-ground faults.[14]

(4) On 331 miles of 132-kv. line on the system of the Public Service Company of Indiana in the 3-year period 1944 to 1946, there were 59 faults, of which 45 (76.3%) were line-to-ground.[42]

A disadvantage of single-pole switching is that each breaker pole must have its own operating mechanism, and a relay scheme must be used that will correctly select the faulted phase or phases. Therefore the switchgear for single-pole rapid reclosing is somewhat more expensive than that for three-pole operation at the same speed. Furthermore, the effects of single-pole switching on the relaying of other lines and on inductive interference with telephone lines must be considered.

Single-pole high-speed reclosing was first used in 1941 on a 132-kv. line of the Public Service Company of Indiana.[17] In that installation, the relays were arranged to trip and reclose one pole for a line-to-ground fault, to trip and lock out all poles if the fault should persist, and to trip and lock out all poles for all faults involving more than one conductor. Later, three-pole reclosing was provided for multiphase faults in addition to the single-pole reclosing for line-to-ground faults. In 3 years' (1944 to 1946) operating experience[42] with five 132-kv. lines of 331 miles total length, equipped with single-pole reclosing breakers, 52 reclosures occurred, of which 41 (78.8%) were successful; the arc was re-established in 6 cases (11.5%); and 5 faults (9.6%) were permanent. Forty-five of the faults were line-to-ground, and the record of them shows somewhat better performance: there were 38 successful single-pole reclosures (84.4%), 4 in which the arc was re-established (8.9%), and 3 permanent faults (6.7%).

Analysis. The power limits obtainable with single-pole switching can be computed by the same procedure that is used in the case of three-pole switching. The only new feature is the way of representing the circuit when one or two wires are open. As explained in Chapter VI, one open conductor is represented by a parallel connection of the three sequence networks; two open conductors, by a series connection. (See Vol. I, Chapter VI, Fig. 25, parts *b* and *c*.) These connections are made at two terminals on each side of the open circuit on the "hot" side of each network—not between the "hot" side and neutral, as for representing short circuits.

---

‡The transient torques produced in turbine generator shafts and couplings by transmission-line reclosings are advantageously found by use of an electrical analogue computer.[32, 44]

In single-pole switching, the faulted wire or wires are actually opened at both ends. If the shunt capacitance of the line is negligible, the effect of the open line on the rest of the system is the same as though the faulted wires were open at only one point and the fault were removed. If the capacitance of the line is considerable, the open circuits at the two ends should be represented separately by connections made through insulating transformers of ratio 1 : 1, and the fault should be represented also during the period of its existence. Usually the simpler connection (corresponding to an open circuit at one end only) will be accurate enough.

EXAMPLE 3

Compare the stability limit of the single-circuit transmission system of Fig. 1*a* when single-pole switching is used with that when three-pole switching is used. The comparison should be made (*a*) for a one-line-to-ground fault and (*b*) for a two-line-to-ground fault, each at the sending end of the line. The switching times are the same as in Example 1, namely, opening in 0.15 sec. and reclosing in 0.35 sec. from the instant of occurrence of the fault.

Solution. *Network reduction.* (1) *Two-line-to-ground fault.* The reduction for this condition was carried out in Example 1, Fig. 3. The shunt negative- and zero-sequence reactances, measured at the point of fault, are $X_2 = 13.33\%$ and $X_0 = 8.33\%$, respectively. The transfer reactance between generators is 216%.

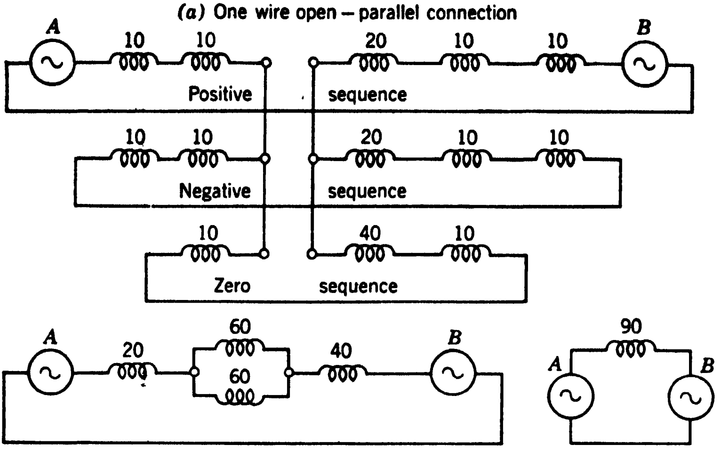
(2) *One-line-to-ground fault.* The fault shunt is $X_2 + X_0 = 13.33 + 8.33 = 21.66\%$. This is connected in shunt with the positive-sequence network instead of the 5.12% shunt of Fig. 3. A Y-Δ conversion yields a transfer reactance of $20 + 40 + 20 \times 40/21.66 = 60 + 36.9 = 96.9\%$.

(3) *One wire open.* Since capacitance is being neglected, the wire will be assumed open at one end only. This condition is represented by a parallel connection of the three sequence networks at the point of open circuit, as shown in Fig. 5*a*. The negative- and zero-sequence networks reduce to reactances of 60% each, and the parallel combination of these is placed in series with the positive-sequence network at the point of open circuit. The transfer reactance is 90%.

(4) *Two wires open.* This condition is represented by a series connection of the three sequence networks at the point of fault, as shown in Fig. 5*b*. The open circuit is therefore represented by insertion of 120% reactance in series with the positive-sequence network. The transfer reactance is 180%.

(5) *Normal condition.* From Example 1, Fig. 3, the transfer reactance is 60%.

Amplitudes of power-angle curves, equal to 1.1 divided by the value of *(a)* One wire open – parallel connection



(b) Two wires open – series connection

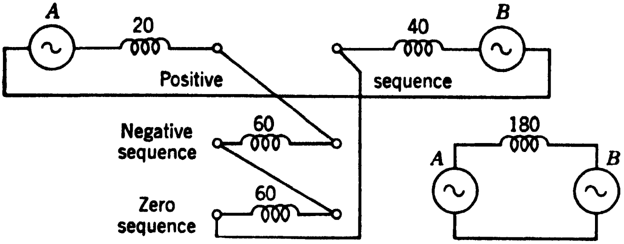


FIG. 5. Network reduction for one or two wires open (Example 3).

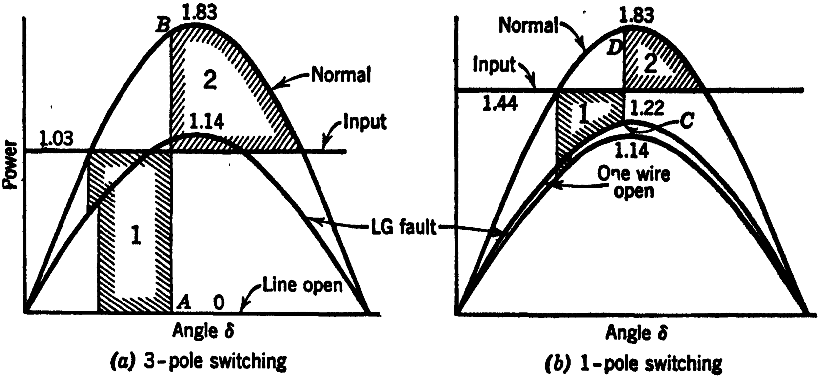
transfer reactance in per unit, are listed in Table 6. The power-angle curves for a line-to-ground fault and both kinds of switching are plotted in Fig. 6; those for a two-line-to-ground fault with three-pole switching, in Fig. 1.

TABLE 6

AMPLITUDES OF POWER-ANGLE CURVES IN PER UNIT (EXAMPLE 3)

Condition	LG Fault		2LG Fault	
	3-pole Switching	*1-pole Switching*	*3-pole Switching*	*1-pole Switching*
Before fault	1.83	1.83	1.83	1.83
Fault on	1.14	1.14	0.51	0.51
Line open	0	1.22	0	0.61
Line reclosed	1.83	1.83	1.83	1.83

Point-by-point computation of swing curves. For a two-line-to-ground fault with three-pole switching, the computation was shown in detail in Example 1. For the other three cases, the computation is similar, but, in order to save space, is not shown. The power limits thus found are listed in Table 7. The increase in stability limit attributable to changing from three-pole to single-pole switching is greater for a line-to-ground fault than for a two-line-to-ground fault although the increase for a two-line-to-ground fault is considerable.



(*a*) 3-pole switching

(*b*) 1-pole switching

FIG. 6. Comparison of transient stability limits for three-pole and single-pole switching. One-line-to-ground fault on a single tie line. Nine-cycle clearing and 21-cycle reclosing in both cases. (Example 3)

TABLE 7

TRANSIENT POWER LIMITS, THREE-POLE AND SINGLE-POLE SWITCHING (EXAMPLE 3)

Type of Fault	Kind of Switching	
	3-pole	*1-pole*
LG	1.03	1.44
2LG	0.90	1.07

Deionization time. In applying high-speed reclosure it is important to know for how long a time a line must be de-energized in order to allow such complete deionization of the arc that it will not restrike when normal voltage is reapplied. Information on deionization time is available from two series of laboratory tests, one reported by Griscom and Torok[2] in 1933, the other by Sporn and Prince[10] in 1937. A partial check on the laboratory tests is provided by operating experience with rapid reclosure and by field tests.

The test circuit used by both groups of investigators is shown in Fig. 7. The arc is initiated by placing a fine piece of wire across the gap (or insulator string) and closing breaker 1. This breaker is immediately tripped by an overcurrent relay. Shortly afterward breaker 2 is closed, reapplying voltage, which may be higher than the voltage used to start the arc. The time interval between the opening of breaker 1 and the closing of breaker 2 can be adjusted by means of cams. Thus a breaker capable of high-speed reclosing is not required for these tests.

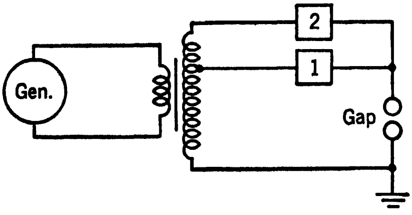


FIG. 7. Test circuit for determining the deionization time of a gap.

The deionization time depends on circuit voltage, conductor spacing or gap length, fault current, fault duration, wind speed, and precipitation. Even if all these factors are constant, however, the deionization time still varies in a random manner through a wide range--for example, from 2 to 10 cycles. If a large number of tests are made with the same dead time, the probability of restriking can be determined. After this procedure has been repeated for different values of dead time, a curve of probability of restriking can be plotted as a function of the dead time. The dead time afforded by rapid-reclosing circuit breakers on a transmission system should be long enough to give a low probability of restriking, say 5% or less.

Of the several factors listed in the last paragraph which affect deionization time, line voltage is the most important. The higher the voltage, the more time is required for deionization. Table 8 gives typical values of deionizing times for 5% probability of restriking.

TABLE 8

TYPICAL ARC-DEIONIZING TIMES[18]

Line-to-Line Voltage (r.m.s. kv.)	Deionizing Time (cycles on 60-c.p.s. basis)
23	4
46	5
69	6
115	8 5
138	10
161	13
230	18

The time required for deionization is slightly lengthened by an increase of arc current or of arc duration or by the presence of rain. The time is slightly shortened by an increase of gap length or of wind speed. The changes due to these factors, however, are small compared with the random variations which occur even when these factors are constant.

The operating experience of the American Gas and Electric Company[14] with three-pole reclosing on a 132-kv. transmission system showed that about 90% of the reclosures were successful with a dead time of 12 cycles. One failure was caused by mechanical damage to the line. Other failures may have been caused by multiple lightning strokes.

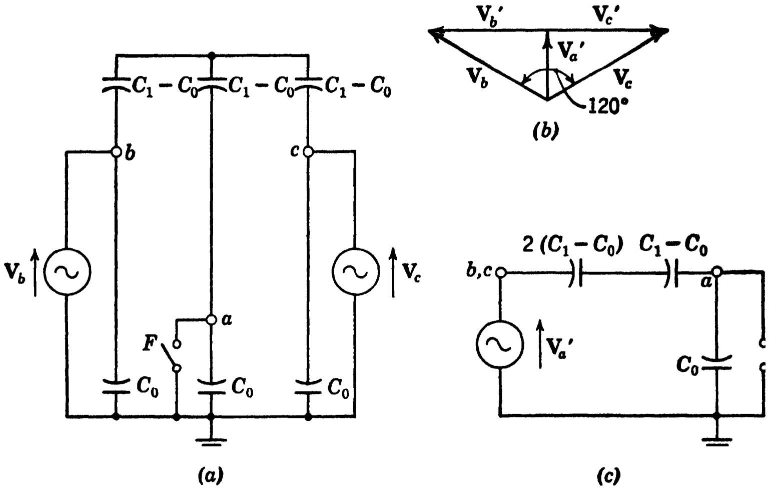


FIG. 8. Circuits used in derivation of expressions for arc current and voltage in case of single-pole clearing. (Adapted from Ref. 19 by permission)

Effect of single-pole switching on deionization. If single-pole switching is used, especially on long high-voltage lines, the faulted conductor should be disconnected somewhat longer than is necessary when three-pole switching is used, in order to obtain equal probability of successful reclosure. The reason is that, while the faulted wire or wires are switched off, capacitive coupling between the sound wire or wires and the faulted wire or wires tends to maintain the arc from line to ground. The theoretical basis for these statements will be shown by repeating a derivation given by H. A. Peterson.[19]

Figure 8*a* shows the equivalent circuit for a line-to-ground fault on wire *a*. Zero-sequence capacitance of the protected section of transmission line is represented by the Y-connected grounded capacitors C_0, and positive-sequence capacitance by these in parallel with additional Y-connected ungrounded capacitors $C_1 - C_0$. Voltages $\mathbf{V}_b$ and $\mathbf{V}_c$ are applied to wires b and c, respectively. Wire a is disconnected from the source of power and is grounded through switch F, representing the fault, as long as the fault persists.

The applied voltages $\mathbf{V}_b$ and $\mathbf{V}_c$ are resolved into components as shown in Fig. 8*b*. Components $\mathbf{V}_b'$ and $\mathbf{V}_c'$, which are equal and opposite, have no effect on the current or voltage of wire a. Component $\mathbf{V}_a'$ is the same in phase b as in phase c; therefore, points b and c may be combined, giving the single-phase circuit of Fig. 8*c*. The magnitude of $\mathbf{V}_a'$ is $E/2$, where E is the normal line-to-neutral voltage.

With switch F closed, a current flows through it to ground, equal to the arc current which must be extinguished before conductor a can be reconnected to the power source. This current is

$$I_f = \frac{E/2}{\dfrac{1}{\omega(C_1 - C_0)} + \dfrac{1}{2\omega(C_1 - C_0)}} = \frac{\omega(C_1 - C_0)E}{3} \qquad [1]$$

The normal positive-sequence charging current per phase of the protected line section is

$$I_{nc} = \omega C_1 E \qquad [2]$$

Therefore the arc current, as a fraction of normal charging current, is

$$\frac{I_f}{I_{nc}} = \frac{C_1 - C_0}{3C_1} \qquad [3]$$

A typical value of C_0/C_1 for an overhead line is 0.6. If this value holds,

$$\frac{I_f}{I_{nc}} = \frac{1 - 0.6}{3} = 0.133 \qquad [4]$$

That is, the arc current to be extinguished is 13% of the normal charging current of the protected line section. It is therefore proportional to the length of the section and to the line voltage.

The steady-state recovery voltage V_a appearing across switch F after the extinction of the arc is

$$V_a = \frac{\dfrac{1}{\omega C_0}\dfrac{E}{2}}{\dfrac{1}{2\omega(C_1 - C_0)} + \dfrac{1}{\omega(C_1 - C_0)} + \dfrac{1}{\omega C_0}} = \frac{C_1 - C_0}{2C_1 + C_0}E \qquad [5]$$

Again assuming $C_0 = 0.6C_1$,

$$\frac{V_a}{E} = \frac{1 - 0.6}{2 + 0.6} \quad 0.154 \tag{6}$$

That is, the voltage on wire *a* due to capacitive coupling after extinction of the arc is 15% of normal line-to-neutral voltage.

In similar manner it can be shown that in a two-line-to-ground fault, when the faulted wires are switched off, the current in each arc to ground is equal to the current in a line-to-ground fault. Furthermore, the voltage on the conductor whose arc goes out first is the same as the voltage in the case of a line-to-ground fault. However, the arc current of the last arc to go out is increased when the first arc is extinguished. It increases to

$$\frac{I_f}{I_{nc}} = \frac{C_1 - C_0}{2C_1 + C_0} \tag{7}$$

which, if $C_0 = 0.6C_1$, becomes

$$\frac{I_f}{I_{nc}} = 0.154 \tag{8}$$

The voltages of the faulted phases, after both arcs have been extinguished, are

$$V_b = V_c = \frac{C_1 - C_0}{C_1 + 2C_0} V_a \tag{9}$$

If $C_0 = 0.6C_1$,

$$V_b = V_c = 0.18E \tag{10}$$

Therefore, deionization times of two-line-to-ground faults may be expected to be somewhat longer than those of one-line-to-ground faults.

Transient recovery voltages are higher than the sustained voltages computed above, particularly if restriking should occur while the faulted conductors are switched off.

Experimental proof that a faulted high-voltage line must remain disconnected a longer time to permit sufficient deionization of the arc if single-pole switching is used than if three-pole switching is used was obtained in some tests made on a 71-mile 220-kv. line.[45] Three-pole reclosing was unsuccessful with 6 cycles dead time but was successful at 12 and 14 cycles. Single-pole reclosing was unsuccessful at 13.7 cycles but was successful at 18 cycles. In the single-pole reclosing tests, evidence of an arc persisting about 11 cycles after cessation of the main fault current was provided by oscillograms and high-speed motion pictures.

Thommen[39] calculated that on an 800-km. 400-kv. line the capacitively fed arc current would be 70 to 440 amp., and he suggested that, in order to accomplish successfully single-pole reclosing of such high-voltage lines, it might be necessary either to split the line into shorter sections or to ground the faulted conductor during the dead time. The execution of his second suggestion would greatly complicate the switching scheme.

No difficulty regarding deionization has been experienced with 35-cycle single-pole reclosing of 100-mile 132-kv. lines.[42]

Although, from the standpoint of arc deionization, single-pole reclosing requires a longer dead time than three-pole reclosing, yet, from the standpoint of system stability, a much longer time is permissible for single-pole reclosing than for three-pole reclosing.

It is conceivable that a breaker could be controlled so as to reclose faster after three poles have been tripped than after only one pole has been tripped.

Multiple lightning strokes.[21] Permanent faults and insufficient time for deionization are probably not the only causes of unsuccessful reclosure. Field observations of lightning have shown that many lightning strokes actually consist of several successive strokes along the same path. The number and spacing of the component strokes vary through a wide range of values. Some multiple strokes last as long as 1 sec. Multiple strokes may cause occasional restriking of fault arcs despite the fact that normal voltage is removed long enough to ensure arc extinction under laboratory conditions. Exact information regarding the effect of multiple lightning strokes on the success of high-speed reclosing is not available.

Circuit breakers for rapid reclosing must meet two requirements not demanded of breakers for nonreclosing service. First, in order to handle occasional permanent faults, the breaker must be capable of interrupting fault current twice or more in rapid succession (depending upon the selected duty cycle) instead of twice 15 sec. apart (as in the standard duty cycle). Second, the breaker must be provided with a suitable operating mechanism and control circuits which, after tripping, will automatically reclose the breaker at high speed and which, if necessary, will trip it a second time.

In order to meet the first requirement—namely, the repeated interruption of fault current—an oil circuit breaker must be equipped with modern arc-rupturing devices, such as "De-ion" grids or oil-blast contact assemblies (see Chapter VIII). When such devices are employed, the contamination of the oil is minimized or the contaminated oil is flushed from the arc path, leaving the path in good condition for another arc interruption. Air-blast circuit breakers are well suited for reclosing service, because fresh air, blown through the arc space, rapidly restores the space to its original condition.

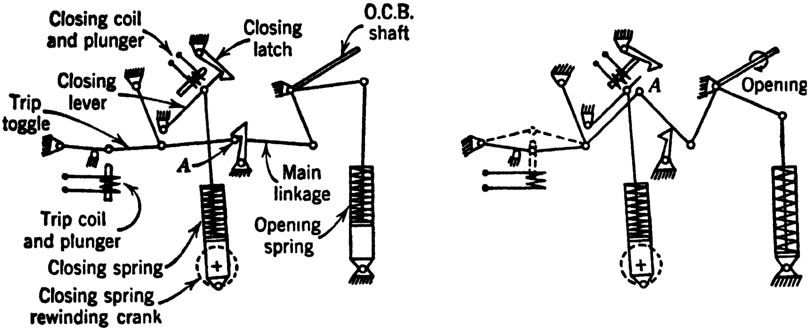
Despite the suitability of modern power circuit breakers for reclosing service, their interrupting ratings are reduced when they are used in such service. The current or kva. interrupting rating of a breaker for reclosing service is found by multiplying its standard interrupting rating (based on the standard operating duty of CO–15 sec.–CO) by a *derating factor* dependent upon the duty cycle and upon the current interrupted, as given in the Standards.§ For example, the factor for opening, reclosing, and reopening with no intentional time delay between operations is 95% for currents up to 15,000 amp. and decreases to 65% at 60,000 amp.

Operating mechanisms. In order to meet the second requirement for rapid-reclosing circuit breakers, special operating mechanisms are often used which give higher speeds than those attainable with standard closing solenoids. To close a large breaker rapidly requires much power. Economical distribution of this power demands that the energy for one or more closing operations be stored near the breaker. The energy can be stored conveniently either in springs or in compressed-air reservoirs. It can be released rapidly for closing the breaker and replaced slowly (at low power) by a small electric motor which rewinds the springs or drives an air compressor.

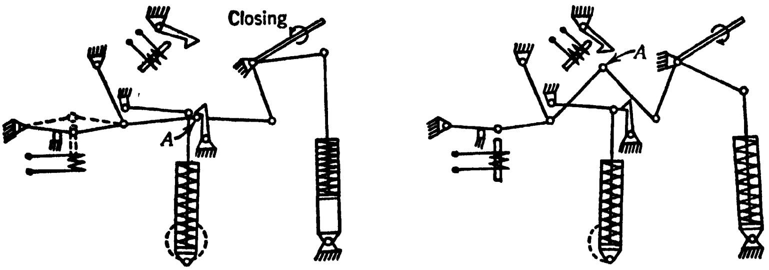
One type of *spring-actuated reclosing mechanism*[22, 28] is shown schematically in Fig. 9. It has two compression springs, one for opening the breaker and one for reclosing it, and permits the following operations to take place without the necessity of recharging the springs: first opening, reclosing, and second opening. Figure 9*a* shows the mechanism in the closed position. Both springs are charged in readiness for the opening cycle. The breaker is held closed against the force of the opening spring by the trip toggle and by the latch at *A*. Upon the occurrence of a fault, the trip-coil plunger trips the toggle, allowing pin *A* of the main linkage to move to the left and escape from the latch. The opening spring opens the breaker by turning the O.C.B. shaft clockwise, and brings pin *A* into the vicinity of the closing lever, as shown in Fig. 9*b*. In the meantime the trip toggle has reset. Reclosing is initiated by the energizing of the closing coil, whose plunger releases the closing latch. The closing spring then closes the breaker by counterclockwise rotation of the O.C.B. shaft

§See Ref. K9 of Chapter VIII.

(see Fig. 9*c*). The other latch then re-engages pin *A*. The closing spring is powerful enough to recharge the opening spring in readiness for a second opening. If the fault is still present, the protective relays again energize the trip coil, releasing the trip toggle. Pin *A* is freed from the closing lever, and the breaker opens, the mechanism going



(a) Breaker closed *(b)* Breaker opened the first time



(c) Breaker reclosed *(d)* Breaker opened the second time

FIG. 9. A spring-actuated mechanism for rapid reclosing of circuit breakers. (From Ref. 22 by courtesy of Pacific Electric Manufacturing Corporation)

to the position shown in Fig. 9*d*. Both springs are now discharged. A motor turns the closing-spring rewinding crank one revolution, thereby resetting the closing lever on the closing latch and charging the closing spring. When the breaker is closed and remains closed, the motor again turns the crank one revolution, bringing the mechanism into the original position (Fig. 9*a*), ready for another immediate-reclosing cycle.

A typical *pneumatic breaker-operating mechanism*[20] suitable for reclosing service is shown in Fig. 10. The breaker is opened by springs (not shown in the figure) and is closed by the action of an air cylinder and piston, which pulls down the operating rod against the force of the opening springs. When it is desired to close the breaker, the magnetic pilot valve is energized, and this in turn opens the main intake valve to admit air through a throttle valve to the cylinder. The throttle valve, which is mechanically actuated by the motion of the operating lever, regulates the flow of air to the cylinder in order to provide fast closing of the breaker without slamming the contacts together too hard. Near the end of the closing stroke, full air pressure is applied in order positively to close the breaker against possible short-circuit forces and against the full force of the opening springs. At the end of the stroke, the breaker is latched closed (see "Latch" in the figure) and an auxiliary switch de-energizes the magnetic pilot valve, shutting off air to the cylinder. When it is desired to open the breaker, the trip magnet is energized, releasing the latch and also operating a pilot valve which opens an exhaust valve (or dump valve) attached to the operating cylinder. This feature makes the breaker *pneumatically trip-free.*

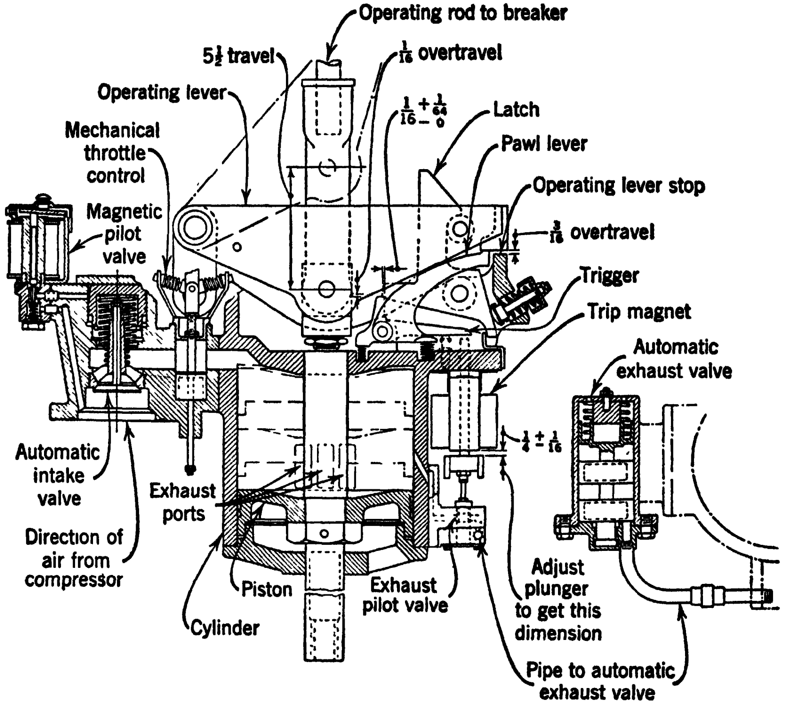

Operating rod to breaker
$5\frac{1}{2}$ travel
$\frac{1}{16}$ overtravel
Operating lever
$\frac{1}{16}{}^{+\frac{1}{64}}_{-0}$
Latch
Mechanical throttle control
Pawl lever
Operating lever stop
Magnetic pilot valve
$\frac{3}{16}$ overtravel
Trigger
Trip magnet
Automatic exhaust valve
$\frac{1}{4} \pm \frac{1}{16}$
Automatic intake valve
Exhaust ports
Direction of air from compressor
Piston
Exhaust pilot valve
Cylinder
Adjust plunger to get this dimension
Pipe to automatic exhaust valve

FIG. 10. Typical pneumatic operating mechanism for oil circuit breakers. (By courtesy of Westinghouse Electric Corporation)

For automatic-reclosing service, special control circuits (described in the next section of this chapter) are employed. After the breaker has been tripped by the protective relays, the trip coil is de-energized and the closing magnet is energized well before the end of the opening stroke, thus reversing the motion of the piston and of the breaker contacts. This performance is illustrated in the time-travel curve of Fig. 11, labelled "Reclosing operation."

An air tank and a motor-driven air compressor are mounted, together with the operating mechanism itself, in a weatherproof housing at the end of the frame of the oil circuit breaker. The tank stores enough energy for at least five closing operations. The maximum operating pressure is 200 lb. per sq. in. Electric heaters are provided in order to prevent freezing of moisture in the air system. Pressure switches start and stop the compressor, sound a low-pressure alarm, and, if the pressure in the tank should become too low to complete a closing operation, open the circuit of the valve magnet.

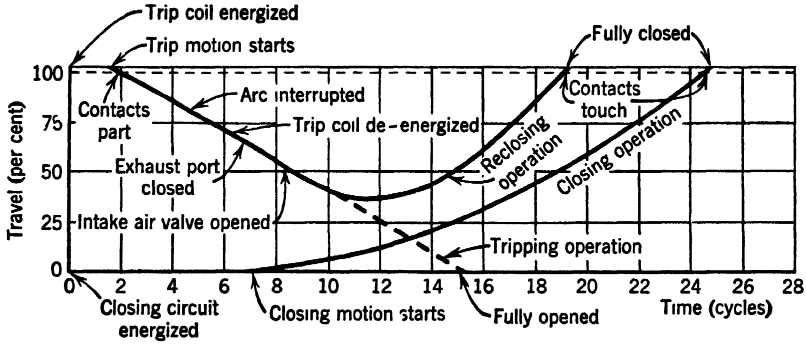


FIG. 11. Typical travel-time curves of oil circuit breaker operated by the pneumatic mechanism shown in Fig. 10: opening, closing, and ultrahigh-speed reclosing. (By courtesy of Westinghouse Electric Corporation)

Single-pole switching requires three operating mechanisms, one for each pole of the circuit breaker. Slower mechanisms can sometimes be used, however, than would be necessary with three-pole switching for the same power limit.

The *reclosing time* of a circuit breaker is the time from the instant when the trip coil is energized to the instant when the arcing contacts touch on the reclosing stroke. Under the assumption that all breakers on a transmission line operate simultaneously, the *dead time*, or time during which the line is de-energized, is equal to the reclosing time of the breakers minus the interrupting time of the breakers.|| Any lack of simultaneity reduces the dead time. A reclosing time of 20 cycles is now common for high-speed reclosing service and can be obtained by mechanisms such as those described above. The interrupting time of these breakers is usually 5 cycles; thus a dead time of 15 cycles is available if the breakers operate simultaneously. Longer reclosing times—for example, 35 and 60 cycles—are used on many breakers, including some equipped for single-pole operation, where a higher speed is not required for stability. Shorter times are readily obtained on pneumatically operated air-blast circuit breakers, the limiting speed of such breakers being determined by the time required for deionization of the line flashover.

Control circuits. The control circuits of a circuit breaker to which automatic immediate single-shot reclosing is applied should include the following features:

1. If the breaker is tripped by the protective relays after having remained closed for a while, it should be reclosed immediately and automatically.
2. If the breaker is tripped through the control switch, it should not be reclosed automatically.
3. If the breaker is tripped by the protective relays immediately after either closing by means of the control switch or automatic reclosing, it should not be reclosed again automatically, because a permanent fault is indicated.
4. In mechanically trip-free breaker-operating mechanisms, the toggle or latch of the closing mechanism must be allowed time to reset itself before the closing coil is energized. Premature energization of the closing coil would move parts of the closing linkage without closing the circuit breaker. This premature action can be prevented by use of a latch-checking auxiliary switch. Such a switch is not needed, however, on pneumatically operated breakers which are not mechanically trip-free.

Figure 12 illustrates typical control circuits which incorporate the features listed above. The circuits are similar to those of Fig. 9, Chapter VIII, with the addition of the parts shown in heavy lines.

If the breaker is tripped by the protective relays after it has remained closed for a while, closing contactor *X* is immediately energized through

---

||For circuit breakers with shunt resistors, the interrupting time used in computing the dead time must be the time when the resistor current is broken and not merely the time when the main fault current is interrupted.

the new reclosing path, in parallel with the control-switch closing contacts *CS-C*, through contacts *T*, *CS-SC*, *CB-LCH*, and *CBbb*; and, accordingly, the breaker is reclosed.

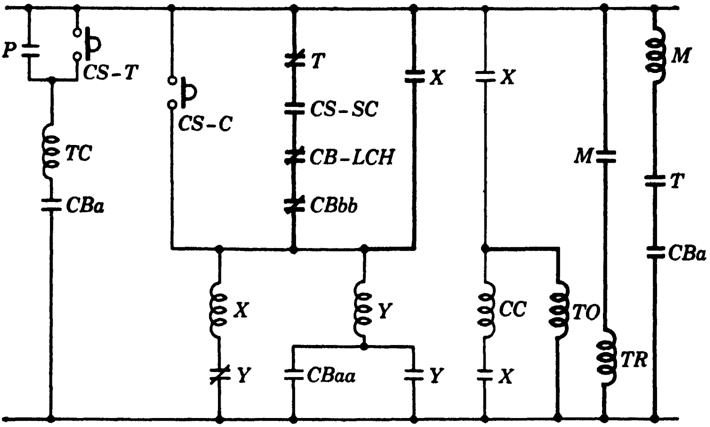


FIG. 12. Control circuits of an electrically operated circuit breaker with reclosing relay for providing a single immediate reclosure.

CBa	Auxiliary switch on circuit breaker, closed when breaker is closed.
CBaa	Auxiliary switch which closes when circuit-breaker mechanism is in operated position.
CBbb	Auxiliary switch which opens when circuit-breaker mechanism is in operated position.
CB-LCH	Circuit-breaker latch-checking contact, which closes when latch is reset.
CC	Closing coil of circuit-breaker mechanism.
CS-C	Control-switch closing contact.
CS-SC	Control-switch slip contact, which closes when handle is turned to "close" and remains closed until handle is turned to "trip."
CS-T	Control-switch tripping contact.
M	Timing motor and contacts.
P	Protective-relay contacts, which close when a fault occurs.
T	Toggle-element contacts, which close when *TO* is energized and remain closed until *TR* is energized.
TC	Trip coil of circuit breaker.
TO	Toggle-element operating coil.
TR	Toggle-element reset coil.
X	Closing contactor.
Y	Releasing contactor.

When the closing coil *CC* is energized through contacts *X*, the operating coil *TO* of the reclosing relay is also energized. This coil opens back contacts *T* in the reclosing path, thereby preventing a second reclosure if the breaker should be retripped immediately.

The same action would occur if the breaker should be tripped automatically right after it had been closed by means of the control switch. Front contacts *T* of the reclosing relay start the timing motor *M*. After expiration of the time for which the motor is adjusted, the timer closes contacts *M*, which energize release coil *TR* of the reclosing relay. This coil recloses back contacts *T* in the reclosing path, thus permitting reclosure in case of subsequent automatic tripping. At the same time front contacts *T* de-energize the timing motor, causing contacts *M* to de-energize coil *TR*.

If the breaker is tripped by means of the control switch, automatic reclosure does not occur, because slip contact *CS-SC* of the control switch opens the reclosing path as soon as the control switch is moved to the "trip" position.

Automatic reclosure cannot occur until the latch in the operating mechanism has reset, because otherwise latching-checking contacts *CB-LCH* are open.

In another type of reclosing relay, a capacitor is charged through a resistor only while the circuit breaker is in the closed position. Automatic reclosure cannot occur if the breaker is tripped before the capacitor has had time to charge to a high enough voltage to operate an auxiliary relay. Thus the resistor and capacitor perform the same function as the timing motor in the reclosing relay previously described.

Relays for rapid reclosing. The necessity of simultaneous operation of the circuit breakers at both ends of a transmission line on which reclosing is used has already been pointed out. Simultaneous tripping of the breakers for all fault locations can be accomplished on some lines by the use of high-speed distance relays set to reach beyond the far end of the line. Where this scheme is not feasible, some form of pilot relaying is used.

If the same protective relays can trip the breaker either in the event of a fault or during large swings and out-of-step operation, it is desirable that reclosure should follow tripping from a fault, but that the breakers should remain open after tripping from swings or out-of-step. The two conditions can be distinguished by the rate of change of impedance, as discussed in Chapter X.

If special protective relays are used to trip the breaker upon occurrence of an out-of-step condition, the control circuits should prevent automatic reclosure after tripping from this cause.

In connection with *single-pole switching*, it is necessary to use a method of relaying that will properly select the breaker pole or poles to be tripped, according to which phase or phases the fault is on and according to the exact method of switching that is desired. It is also necessary to arrange the relay circuits so that all poles are tripped and locked out after an unsuccessful reclosure on any type of fault. In addition, all poles should be tripped and locked out if the back-up relays act to clear an external fault.

The simplest type of single-pole switching is that in which only one pole is opened and reclosed for a one-line-to-ground fault but three poles are opened for faults of other types. Phase faults are cleared, as usual, by high-speed distance relays which are connected so as to trip all three poles of the breaker. These relays are not actuated by one-line-to-ground faults, because the line-to-line voltage is not sufficiently collapsed by such faults. Ground faults are cleared, as usual, by high-speed directional ground relays, operating on zero-sequence current and voltage, because relays operating on phase current and voltage cannot be depended upon to distinguish between normal-load conditions and high-resistance ground faults. Zero-sequence ground relays cannot determine which phase the fault is on. They must, therefore, be supplemented by *phase-selector relays* when single-pole switching is employed.

One type of phase-selector relay that has been used operates according to the phase relations between the zero- and negative-sequence currents.[16] Vectors representing the symmetrical components of current in a line-to-ground fault are drawn in Fig. 13. In the faulted phase the three components of current are equal and in phase, whereas in the unfaulted phases they are equal in magnitude but are 120° apart. The division of the sequence currents between the two ends of a faulted line is usually such that the current vectors at each end do not differ materially from those of the current in the fault itself.

The phase-selector relay consists of three directional elements, each supplied with zero-sequence current and with the negative-sequence current of one phase. Maximum torque occurs when the two currents are in phase with one another. The *a*-phase element operates on currents I_0 and I_{a2}; the *b*-phase element, on I_0 and I_{b2}; and the *c*-phase element, on I_0 and I_{c2}. If a line-to-ground fault occurs on phase *a*, I_0 and I_{a2} are in phase, and the torque of the *a*-phase element closes the front contacts, which are in the trip circuit of the *a*-phase circuit-breaker pole. Since I_0 and I_{b2} are 120° apart, the torque of the *b*-phase element holds the contacts open. The same is true of the *c*-phase element. Likewise, if the fault is on phase *b*, only the *b*-phase element closes its contacts; and if the fault is on phase *c*, only the *c*-phase element closes its contacts. Thus the faulted phase is selected for tripping.

The connections of the phase-selector relay are shown in Fig. 14. Negative-sequence currents are supplied to the selector relay from a negative-sequence filter having a three-phase output. The directional overcurrent ground relay may be polarized either by voltage or by current. This relay determines whether or not the fault is in the tripping direction. The action of the phase-selector relay is independent of the direction to the fault, because a change of direction reverses all components of current with respect to the voltage without altering the phase difference between the zero- and negative-sequence currents.

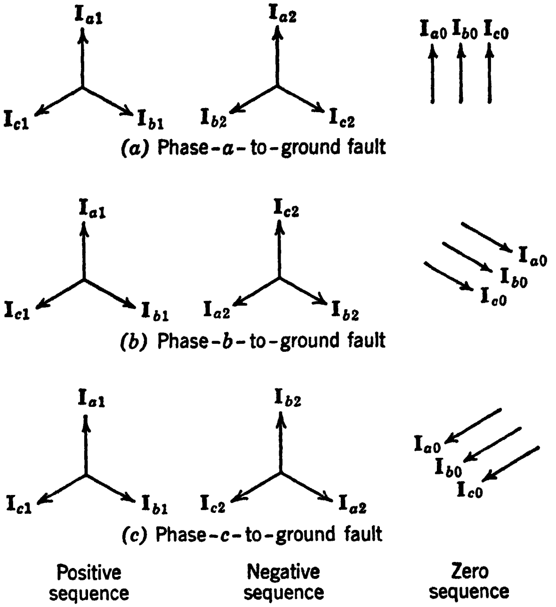


FIG. 13. Sequence current vectors for line-to-ground faults on different phases.

While one pole of the breakers is open, there are zero- and negative-sequence currents in the line having such phase angles that the selector relay selects the open phase. Therefore, there is no tendency to trip the sound phases while one wire is open. During a two-line-to-ground fault the selector relay selects the unfaulted phase. Therefore the phase relay must be given control.

If selective-pole switching is used for all types of fault, the relaying is necessarily more complicated than that just described. One pole must be tripped for line-to-ground or line-to-line faults, two poles for two-line-to-ground faults, and three poles for three-phase faults, second trippings, and back-up protection. The high-speed impedance relays are supplied with star current instead of the usual delta current. This connection gives a balance point the position of which varies according to the type of fault, and the relays must be set to prevent their overreaching on external two-line-to-ground faults. The fact that the balance point moves toward the relay for some faults is unimportant

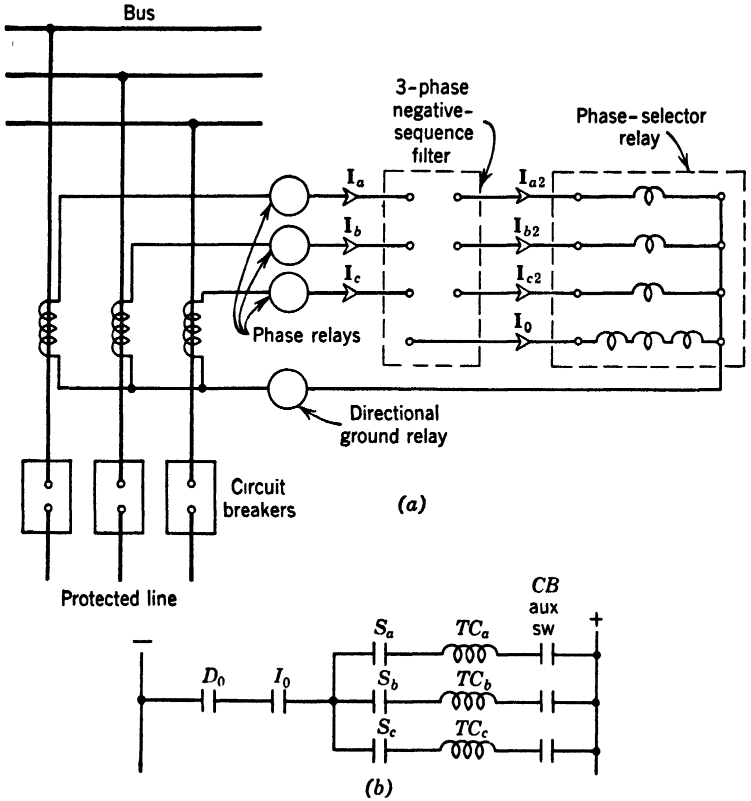


FIG. 14. Simplified diagram of connections of phase-selector relay. (*a*) Current circuits. (*b*) Trip circuits.

with carrier-controlled relays. One-line-to-ground faults are cleared by the ground and phase-selector relays in the manner described in the previous relay scheme. During severe faults one phase-fault relay may operate at the same time, but this relay acts to trip the same pole as the ground relay. On line-to-line faults—for example, on phases *b* and *c*—the phase-*b* impedance relay, which receives *bc* potential, trips pole *b* of the breaker. The ground relays do not operate. On a two-line-to-ground fault on phases *b* and *c*, the phase-*b* impedance relay trips pole *b*, as before. At the same time the ground relay and phase-selector relay select phase *a* and would trip pole *a* of the breaker, did not the operation of the phase relay actuate an auxiliary relay that switches the trip circuit from pole *a* to pole *c*. Thus poles *b* and *c*, the faulted phases, are tripped. Three-phase faults operate all the phase relays, which trip all poles of the breaker. The back-up relays trip all three poles through an auxiliary relay. Some other interlocking features are required which will not be described here.

Results of analyses of stability with reclosure. When the use of rapid reclosure for maintaining stability is considered in connection with an important project, it is desirable to make a thorough stability study for determining the power limits with various types and locations of fault, various kinds of reclosing equipment, and various operating conditions. Or the kind of reclosing equipment required for transmitting a specified amount of power may be determined. In such studies an a-c. calculating board can be used advantageously.

Although complete studies of specific systems are warranted for important projects, they are not always feasible and it is therefore desirable to have on hand results of studies on simple hypothetical two-machine power systems. Such results are useful for rough estimating and for drawing general conclusions as to the effectiveness of various kinds of reclosing equipment when applied to various power-system layouts. Fortunately several such studies have been made.

One such study, described by Crary, Kennedy, and Woodrow,[19] deals with *interconnections between two steam-electric power systems of equal size.* These two systems are connected through an overhead transmission system consisting either of one line or of two lines in parallel. The length of line is 50, 100, 200, or 300 miles. The frequency is 60 c.p.s. Each line has the following constants per mile: $\mathbf{Z}_1 = 0.16 + j0.8$ ohm, $\mathbf{Z}_0 = 0.43 + j2.4$ ohm, $\mathbf{Y}_1 = j5.2 \times 10^{-6}$ mho, $\mathbf{Y}_0 = j3.12 \times 10^{-6}$ mho. Mutual impedance and admittance between lines are neglected. The power system at each end of the transmission line is represented by a synchronous machine having impedances $\mathbf{Z}_1 = \mathbf{Z}_2 = \mathbf{Z}_0 = 0.002 + j0.05$ per unit and inertia constants $H = 20$ per unit on a kilovolt-ampere base of $2.5(\text{kv.})^2$. This base power is equal to the characteristic-impedance, or unity-power-factor, loading of each line. The use of this base makes the impedances independent of the transmission voltage, regardless of whether they are expressed in per unit or in ohms. The voltages back of system impedances are held fixed at values which give unit voltage at each line terminal when the power transfer on each circuit is 1.10 per unit at the sending end.

Faults of various types (line-to-ground, two-line-to-ground, and three-phase) are assumed to occur at the sending end and to be cleared in either 6 or 9 cycles by three-pole or single-pole switching. (These clearing times correspond to breaker interrupting times of 5 and 8 cycles, respectively, plus 1 cycle relay time.) The maximum permissible de-energization time for stability is plotted against receiver-end power in Figs. 15 to 19, inclusive. Each figure is for a different length or layout of the transmission system. Each curve represents a particular type of fault and kind of switching.

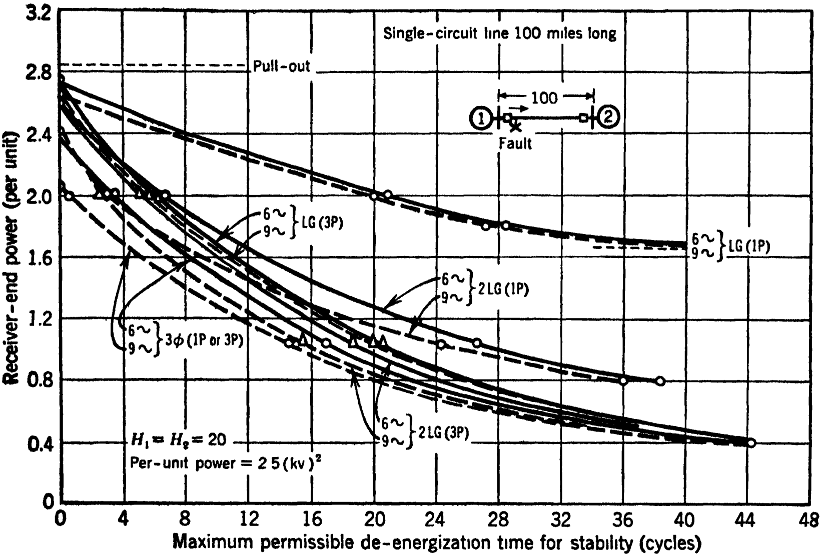


FIG. 15. Stability of 100-mile single-circuit interconnection with reclosure. (From Ref. 19 by permission)

The adopted value of inertia, $H = 20$, requires interpretation. A typical power system has an inertia constant of 5 per unit on its connected kilovolt-ampere generator capacity. Therefore the value $H = 20$ represents a generator capacity of about four times the base power. However, the results can be applied to larger or smaller systems, as follows: Since the time required for the generators to swing through any given angle varies as $\sqrt{H}$, the curves for 6-cycle clearing and $H_1 = H_2 = 20$ can be interpreted for 9-cycle clearing and $H_1 = H_2 = 20 \times (1.5)^2 = 45$ (generator capacity about 9 per unit), provided the

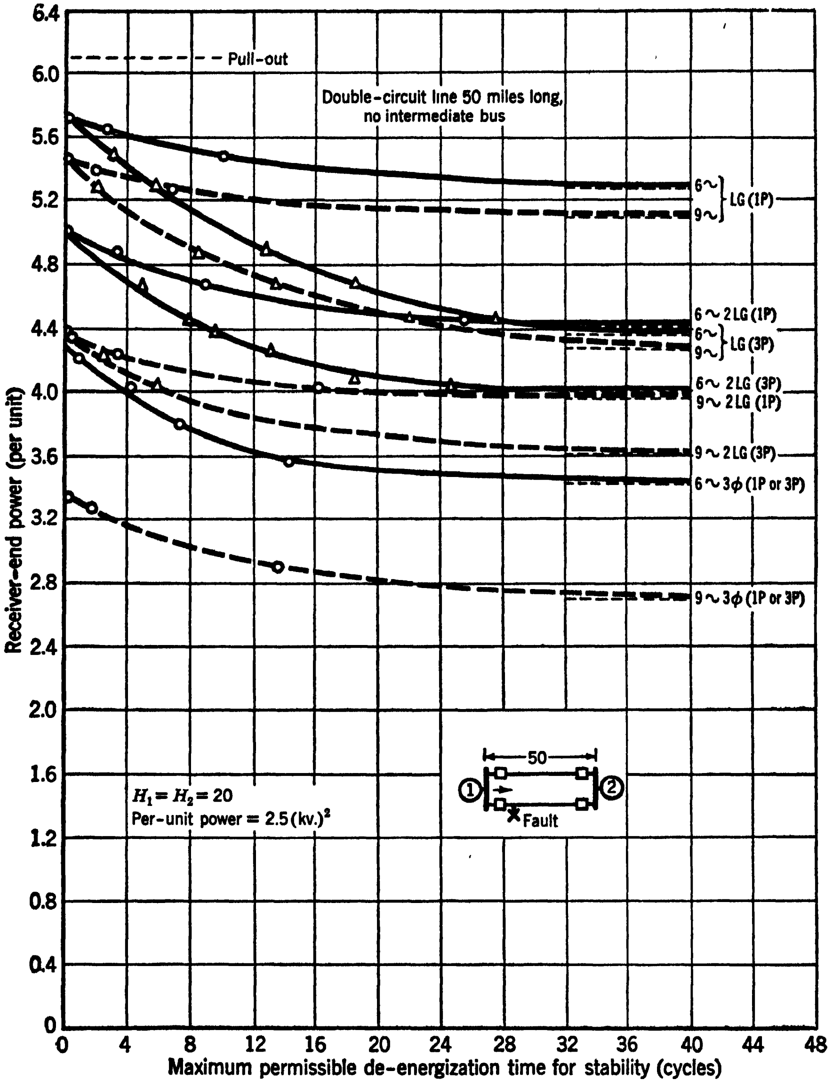


FIG. 16. Stability of 50-mile double-circuit interconnection with reclosure. (From Ref. 19 by permission)

de-energization times given on the curves are increased by a factor of 1.5. Similarly, the curves for 9-cycle clearing and $H_1 = H_2 = 20$ can be interpreted for 6-cycle clearing and $H_1 = H_2 = 20/(1.5)^2 = 8.9$ (generator capacity about 1.8 per unit), provided the de-energization times be divided by 1.5.

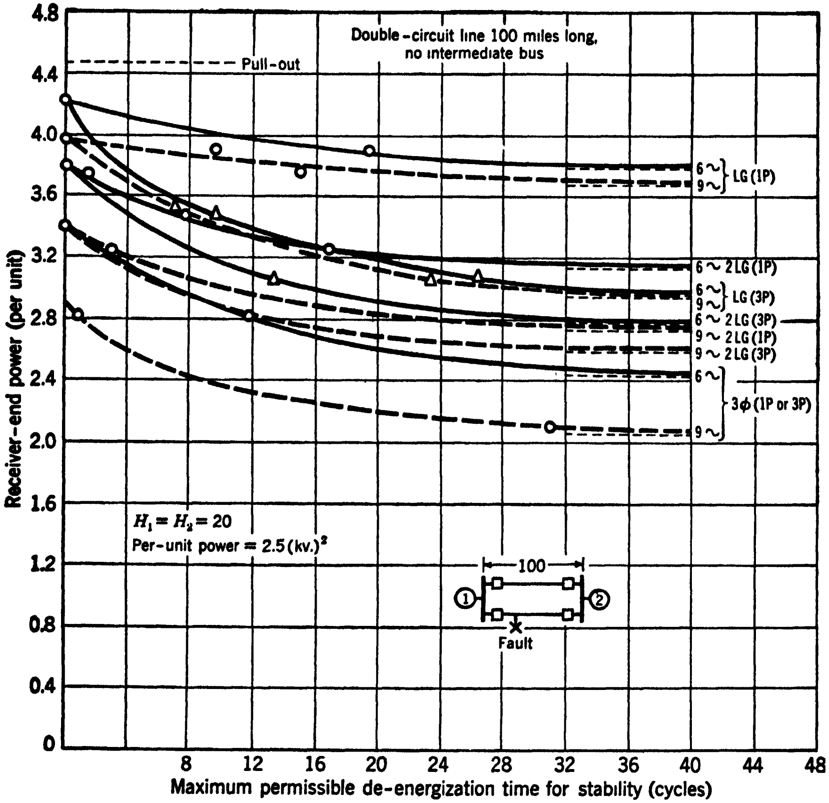


FIG. 17. Stability of 100-mile double-circuit interconnection with reclosure. (From Ref. 19 by permission)

All the curves of Figs. 15 to 19 show that the power decreases as the de-energization time increases. At large values of de-energization time the power approaches the value obtainable without reclosure. In Fig. 15 (for the single-circuit line), this value is zero for a three-phase fault or for three-pole switching. It is finite for the other curves of this figure and for all curves in the figures pertaining to double-circuit lines. The increase of power limit with decrease of de-energization time is less with a double-circuit line than with a single-circuit line,

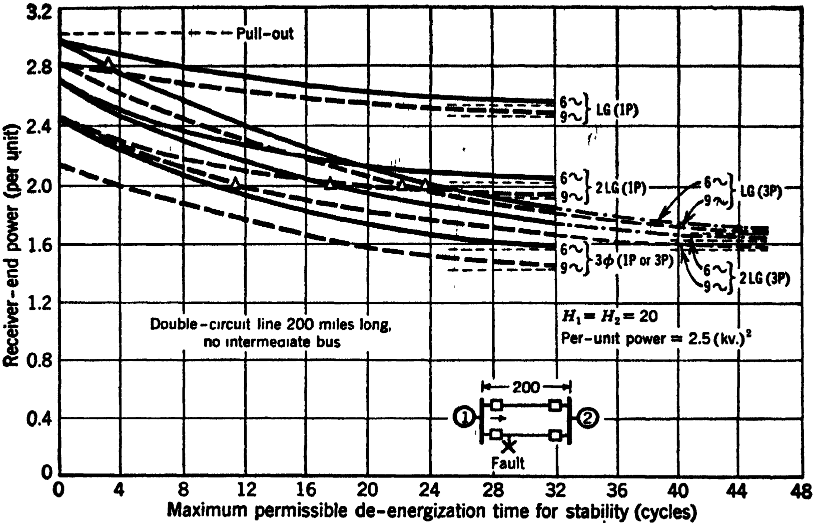


FIG. 18. Stability of 200-mile double-circuit interconnection with reclosure. (From Ref. 19 by permission)

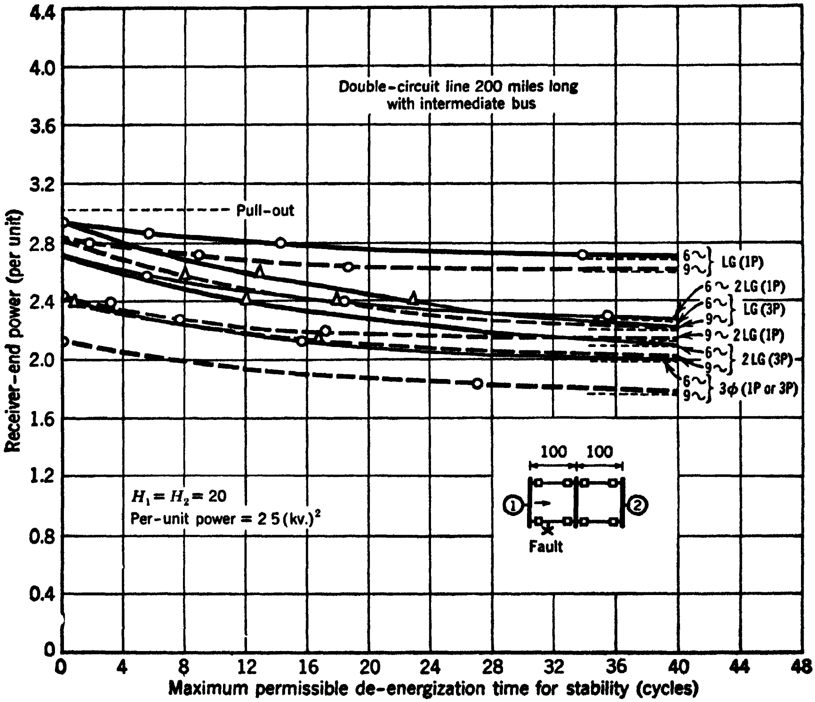


FIG. 19. Stability of 200-mile double-circuit interconnection with intermediate switching station and reclosure. (From Ref. 19 by permission)

and, with the former, is less with short lines than with long lines, and is less with an intermediate switching station than without one.

The effect of the type of transmission system on the power limits obtainable with reclosure can be shown advantageously by plotting power limit as a function of the ratio of normal transfer reactance to the transfer reactance with the faulted circuit open. Such plots are given in Figs. 20 to 22. Four transmission-line layouts are used that have equal transfer reactances (0.3 per unit) under normal conditions but different reactances when the faulted line is open. The systems and their ratios of normal to open-line reactance are as follows:

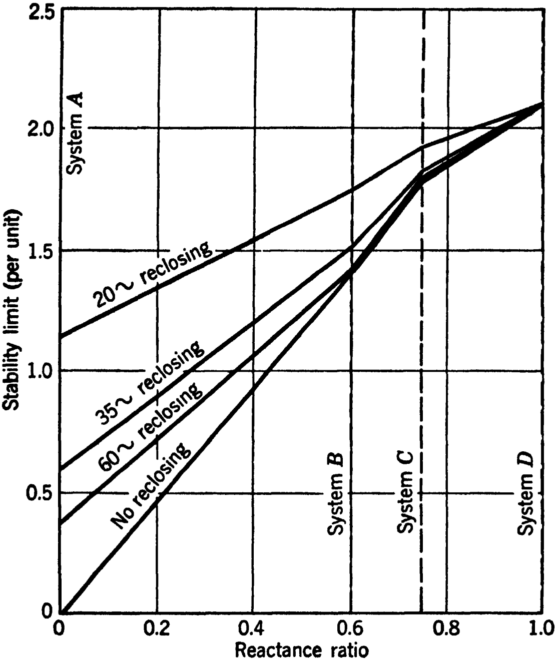


FIG. 20. Stability limits for three-phase faults at sending end, with 9-cycle clearing, as a function of reclosing time and ratio of normal transfer reactance to that with faulted circuit open. (Adapted from Ref. 19 by permission)

A.	100-mile single-circuit line	0
B.	200-mile double-circuit line	0.6
C.	200-mile double-circuit line with switching station at center of line	0.75
D.	Same as system *B* except that the fault is on a stub feeder and is cleared without opening the main transmission lines	1.00

Each figure is plotted for a different type of fault. Each curve is for a different value of reclosing time used in commercially available breakers: 20, 35, or 60 cycles. In every case 9-cycle clearing (1 cycle relay time plus 8 cycles breaker interrupting time) is assumed. The de-energization time is, therefore, the reclosing time less 8 cycles. Data are replotted from Figs. 15, 18, and 19 for systems *A*, *B*, and *C*, respectively. For system *D* data are taken from Fig. 18 at zero de-energization time.

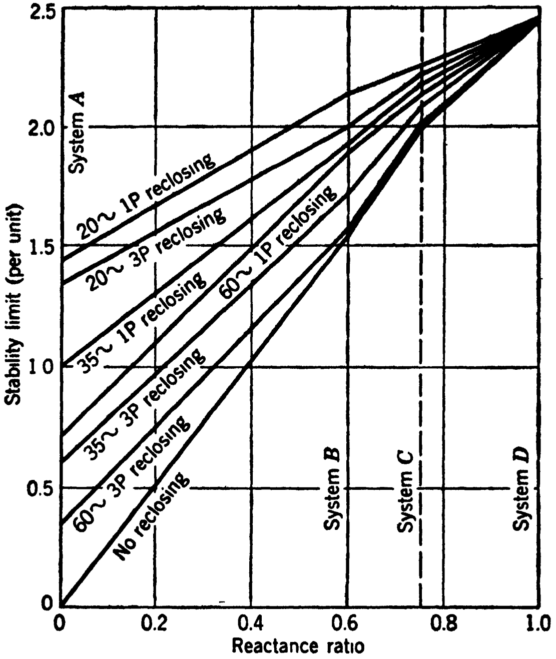


FIG. 21. Stability limits for two-line-to-ground faults at sending end, with 9-cycle clearing, as a function of reclosing time and ratio of normal transfer reactance to that with faulted circuit open. (Adapted from Ref. 19 by permission)

These curves show clearly that, although the power limit increases, the benefit due to reclosure decreases as the reactance ratio increases. On the single-circuit line (system *A*) reclosure greatly aids stability; on the double-circuit line (system *B*) it helps somewhat; on system *C* it helps very little; and on system *D*, not at all.

Figures 20 to 22 show also the relative effects of different reclosing methods and speeds for each type of fault. For example, for a line-to-ground fault (Fig. 22), even 60-cycle single-pole reclosing is better than 20-cycle three-pole reclosing. For a two-line-to-ground fault (Fig. 21), 60-cycle single-pole reclosing is better than 35-cycle three-pole reclosing, but 35-cycle single-pole reclosing is not so good as 20-cycle three-pole reclosing.

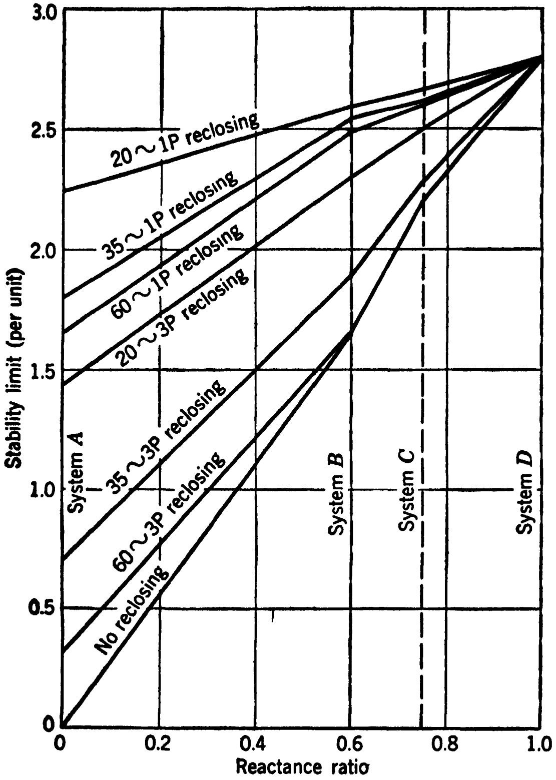


FIG. 22. Stability limits for line-to-ground faults at sending end, with 9-cycle clearing, as a function of reclosing time and ratio of normal transfer reactance to that with faulted circuit open. (Adapted from Ref. 19 by permission)

The curves are so nearly straight that reasonably correct values of power limit can be read from them for systems having other values of reactance ratio than those used in plotting. In the range of reactance ratios from 0 to 0.5, reclosing is very beneficial. Reactance ratios in this range can be obtained through paralleling the principal tie line with a line of higher reactance. The latter line may follow a more roundabout route than the principal tie, or it may be a line of lower voltage. Such a line, even though its reactance is several times as great as that of the principal line, raises the power limit considerably. For example, an added line having 6 times the reactance of the principal tie line gives a reactance ratio of 0.2 on the system under consideration and raises the power limit for a three-phase fault on the principal line, as follows: With no reclosing, the power limit is higher than that obtained with the principal line alone and 60-cycle reclosing. Similarly, with 60-cycle reclosing, the power limit is higher than that obtained with the principal line alone and 35-cycle reclosing. The presence of a parallel high-reactance line may thus render reclosure feasible in cases where the inertia constants are so low that, without the added line, synchronism could not be maintained even by use of the highest reclosing speed available.

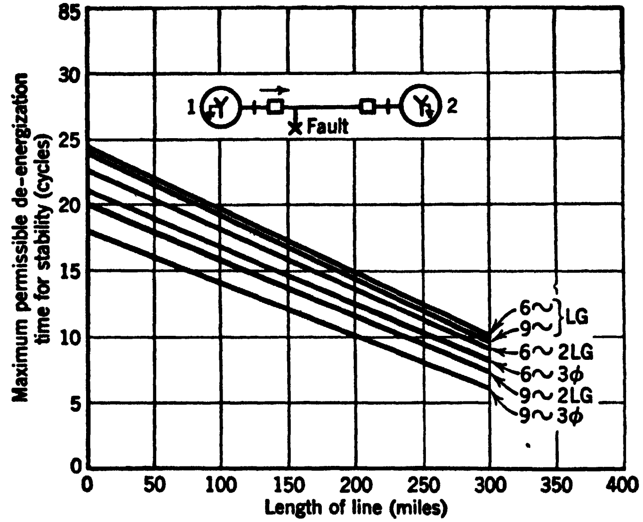


FIG. 23. Single-circuit interconnection, three-pole switching. (From Ref. 19 by permission)

For the single-circuit line, with sending-end power fixed at 1.1 per unit, the maximum permissible de-energization time for stability is plotted as a function of the length of line in miles in Figs. 23 and 24. These figures are for three-pole switching and single-pole switching, respectively. For a three-phase fault, successful reclosure can be expected for line lengths up to 150 and 210 miles with a de-energization time of 12 cycles and clearing times of 9 and 6 cycles, respectively. If the inertia constants are increased from 20 to 45, reclosure will be successful with 9-cycle clearing on line lengths up to 300 miles. (This value is read from the "6~ 3ϕ" curve at a de-energization time of 8 cycles—now representing 12 cycles.) If, on the other hand, the inertia constants are decreased to 8.9, reclosure will be unsuccessful even with 6-cycle clearing and a very short line. These results show that inertia is a very important factor in the success of reclosure.

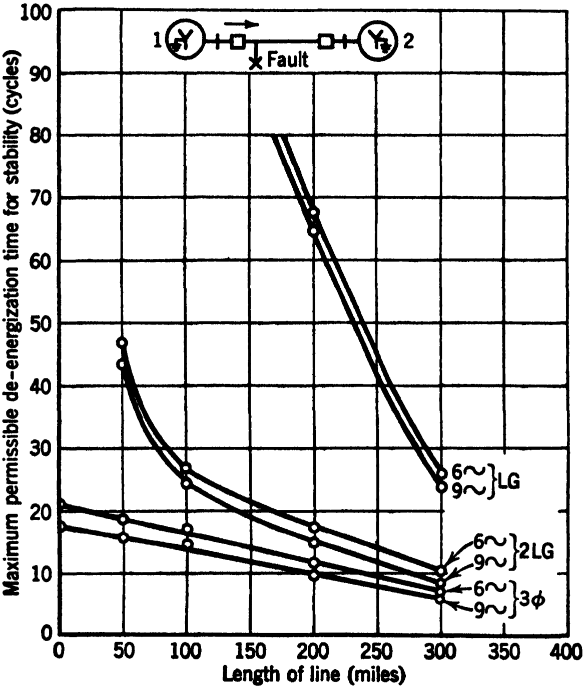


FIG. 24. Single-circuit interconnection, single-pole switching. (From Ref. 19 by permission)

Hydroelectric systems. The inertia constant of hydroelectric generating units is about 3 per unit based on their own ratings. This value of inertia is much too low to permit successful reclosure of a single-circuit line carrying anywhere near the rated output of the hydroelectric station, except for single-pole switching of line-to-ground faults. Figures 25 and 26 show results obtained from calculations on a typical hydroelectric system,[19] consisting of a generating station transmitting power over a single-circuit line to an infinite bus. The transmission-line constants are the same as those used in the study of system interconnections previously considered. Other reactances are as follows, based on the generator kilovolt-amperes: generators, 0.30 per unit; transformers at each end, 0.10 per unit; receiving system, 0.10 per unit. The inertia constant of the hydroelectric generators is 3 per unit. Unit voltage is assumed at both high-voltage terminals. In the figures, P_G denotes the kilowatt rating of the generators in per unit of $2.5(\text{kv.})^2$, and their kilovolt-ampere rating is assumed to be $P_G/0.9$. The sending-end power is taken as $1.1P_G$. Figure 25 shows that, for $P_G = 1$, 9-cycle clearing, and 35-cycle reclosing (27-cycle de-energization time), the maximum permissible length of line is 50 miles. Figure 26 shows that for $P_G = 1$, 6-cycle clearing, and 20-cycle reclosing (15-cycle de-energization time), the length may be increased to 100 miles. For heavier line loadings, the lines must be still shorter. It may be concluded, therefore, that rapid reclosing is not very effective on a single-circuit line carrying the full output of a hydroelectric station. In order to ensure reliable operation, two lines in parallel should be used.

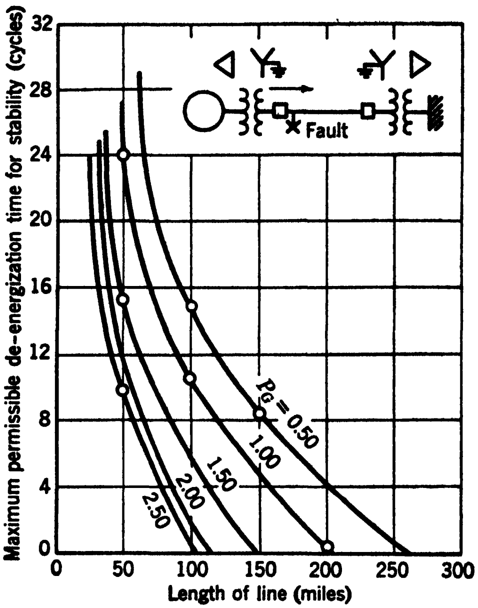


FIG. 25. Hydroelectric system—single-circuit line. Single-pole switching of line-to-ground faults. Nine-cycle clearing. P_G = rated generator output. Curves are for a loading $1.1P_G$. (From Ref. 19 by permission)

Single-circuit interconnections between two steam-electric power systems of equal or unequal size were studied by Parker and Travers.[24] They considered only *two-line-to-ground faults* at the sending end of the interconnecting line, cleared in 0.15 sec. (9 cycles). The following types of switching were considered: one-pole 20-cycle reclosing, three-pole 20-cycle reclosing, one-pole 30-cycle reclosing, and three-pole 30-cycle reclosing. The generating capacity of the sending system was taken as equal to 0.2, 1, or 5 times that of the receiving system. Each system was assumed to consist of the required number of 1,800-r.p.m.

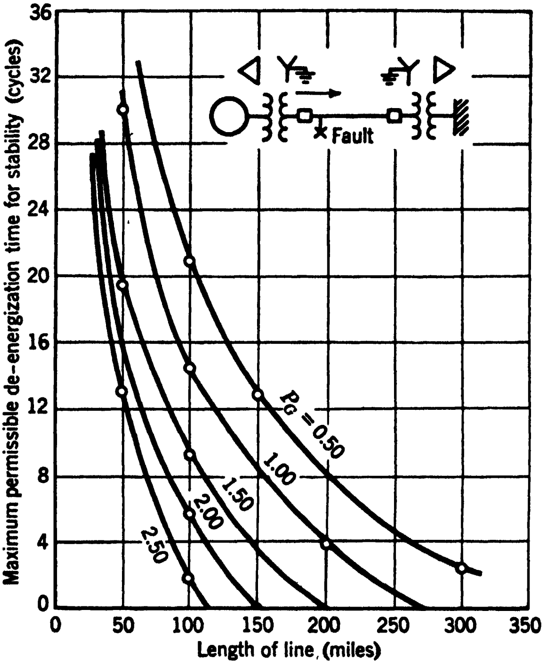


FIG. 26. Hydroelectric system—single-circuit line. Single-pole switching of line-to-ground faults. Six-cycle clearing. P_G = rated generator output. Curves are for a loading $1.1P_G$. (From Ref. 19 by permission)

80%-power-factor machines operating at full kilowatt load and with excitation as required. The constants of these machines in per unit, based on their own ratings, were: $H = 7.4$, $x_d' = 0.23$, $x_2 = 0.15$, $r_1 = 0.009$, and $r_2 = 0.035$. The local loads were of 85% power factor (lagging current). The transmission line was assumed to have the following constants: $x_1 = 0.71$ ohm per mile, $y_1 = 5.8 \times 10^{-6}$ mho per mile, $r_0 = 0.45$ ohm per mile, $x_0 = 2.84$ ohms per mile, $r_1 = 0.35$ ohm per mile or a value which would give 10% loss in the line, whichever gives the smaller value of resistance. It was assumed that the line would be operated at approximately unity-power-factor loading. Transformers at each end of the line were assumed to have a kilovolt-ampere rating equal to the power transmitted in kilowatts, to have a reactance of 0.085 per unit based on their own ratings, and to be connected Δ-Y with the neutrals on the high-voltage side solidly grounded. The sending-end voltage of the line was adjusted to a value 10% higher than the receiving-end voltage. In certain cases this required that reactive power be furnished by the receiver-system generators in excess of the capacity of those generators. In these cases the additional reactive power was assumed to be supplied by synchronous condensers, the inertia of which was neglected.

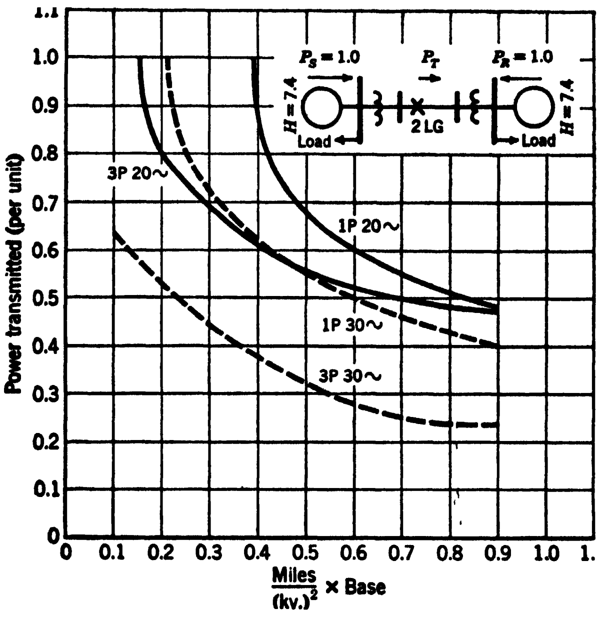


FIG. 27. Transient stability limit for reclosing of a single tie line between two systems with equal steam generating capacity connected. Base equals generating capacity in either system. Per-unit power transmitted is referred to this base. Faults are double-line-to-ground, cleared in 0.15 sec. (From Ref. 24 by permission)

The length of line was varied, with all other conditions fixed, until the critical length was reached where an increase of length would result in instability, and a decrease would give stability. The results of these studies are plotted in Figs. 27, 28, and 29. In each figure the transmitted power in per unit is plotted as a function of the quantity "(miles/kv.^{2}) × base." The base is the generating capacity in megawatts.

In order to make the results readily usable for other ratios of sending-end to receiving-end inertia than 0.2, 1, and 5, H. N. Muller, Jr. (in discussion of Ref. 24) replotted the data of Figs. 27, 28, and 29 in a different manner, as shown in Figs. 30 to 33, inclusive.

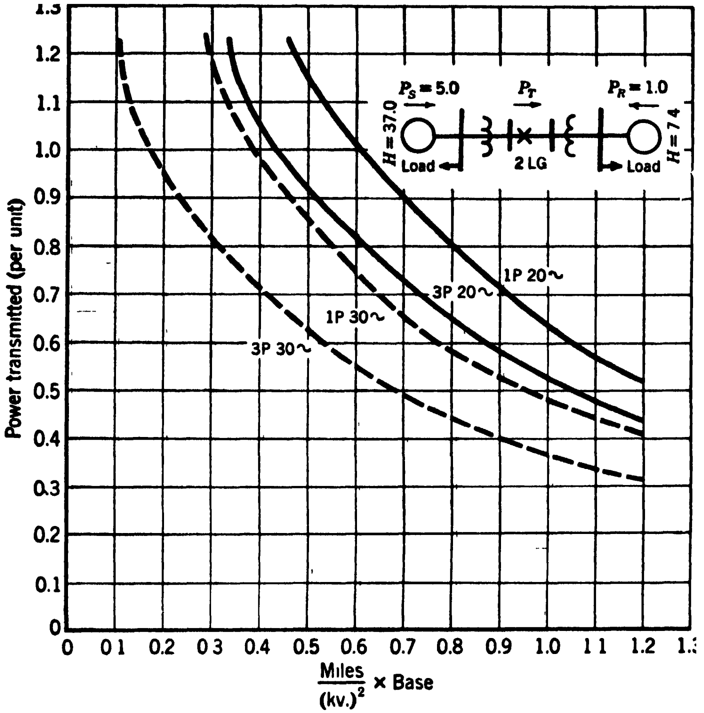


FIG. 28. Transient stability limit for reclosing of a single tie line between two systems, with the steam-electric generating capacity of the sending-end system five times that of the receiving-end system. Base equals generating capacity of the receiver system. Per-unit power is referred to this base. Faults are double-line-to-ground, cleared in 0.15 sec. (From Ref. 24 by permission)

EXAMPLE 4

It is desired to transmit 22 Mw. over a 69-kv. single-circuit line 57 miles long from a power system having steam-electric generating capacity of 64 Mw. to a second power system having a steam-electric generating capacity of 25 Mw. What type and speed of reclosure are required to maintain synchronism after the occurrence of a two-line-to-ground fault?

Solution. Base power = P_R = 25 Mw.

The transmitted power is P_T = 22 Mw./25 Mw. = 0.88 per unit.

(Miles/kv.^{2}) × base = $[57/(69)^2] \times 25 = 0.30$.

Inertia ratio is $H_S/H_R = P_S/P_R = 64/25 = 2.56$.

Figures 30 to 33 inclusive are entered with abscissa 2.56 and ordinate 0.88, and in each figure the value of (miles/kv.^{2}) × base read by interpolation between the curves is compared with the given value, 0.30. If the value read is greater than 0.30, the system is stable; less than 0.30, unstable. Figure 30 shows that three-pole 30-cycle reclosure results in instability. Figures 31 and 32 show that either three-pole 20-cycle or single-pole 30-cycle reclosure gives stability with a reasonable margin. Figure 33 shows that 20-cycle single-pole switching produces stable operation with considerable margin.

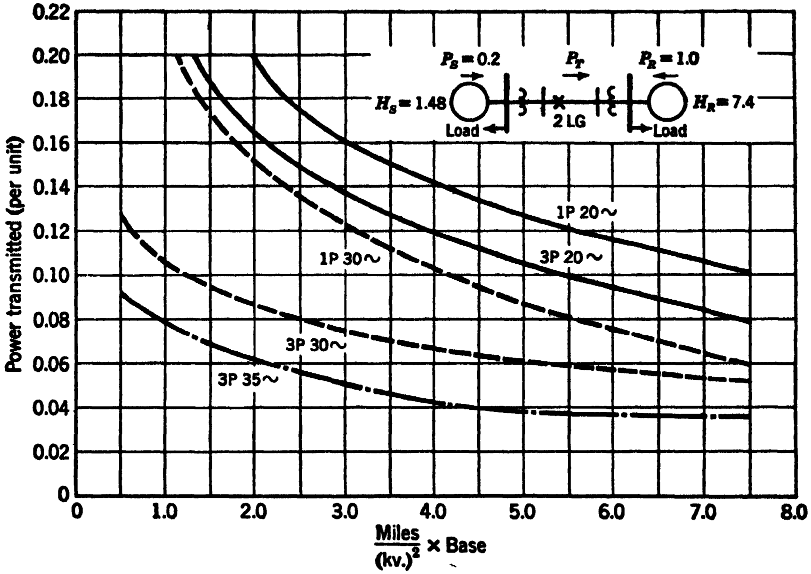


FIG. 29. Transient stability limit for reclosing of a single tie line between two systems with the steam-electric generating capacity of the receiving-end system five times that of the sending-end system. Base equals generating capacity of the receiver system. Per-unit power is referred to this base. Faults are double-line-to-ground, cleared in 0.15 sec. (From Ref. 24 by permission)

The choice between three-pole and single-pole switching as affected by the basis of system design with respect to stability.[17] It has already been noted that single-pole switching greatly increases the power limit for line-to-ground faults over that obtained with three-pole switching at the same speed, but that the corresponding gain for two-line-to-ground faults is not nearly so great. In the past it has

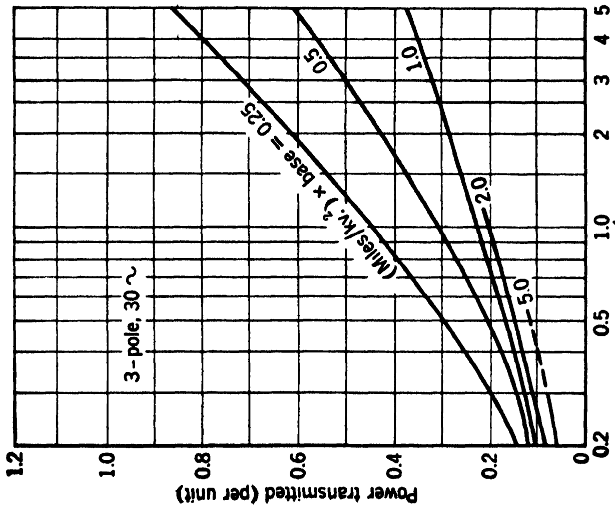

3-pole, 30~
(Miles/kv.²) × base = 0.25
0.5
1.0
2.0
5.0
Power transmitted (per unit)
0
0.2
0.4
0.6
0.8
1.0
1.2
0.2
0.5
1.0
2
3
4
5
M_S/M_R

FIG. 30.

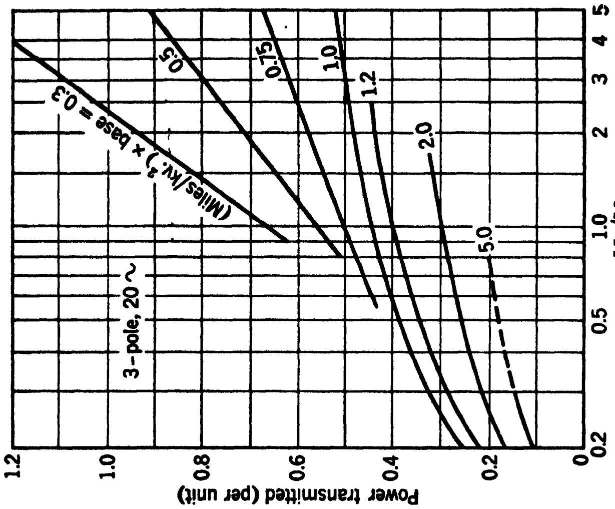

3-pole, 20~
(Miles/kv.²) × base = 0.3
0.5
0.75
1.0
1.2
2.0
5.0
Power transmitted (per unit)
0
0.2
0.4
0.6
0.8
1.0
1.2
0.2
0.5
1.0
2
3
4
5
M_S/M_R

FIG. 31.

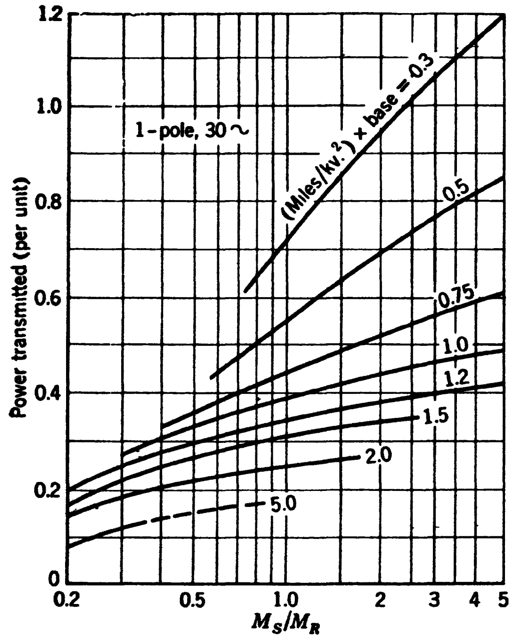


FIG. 32.

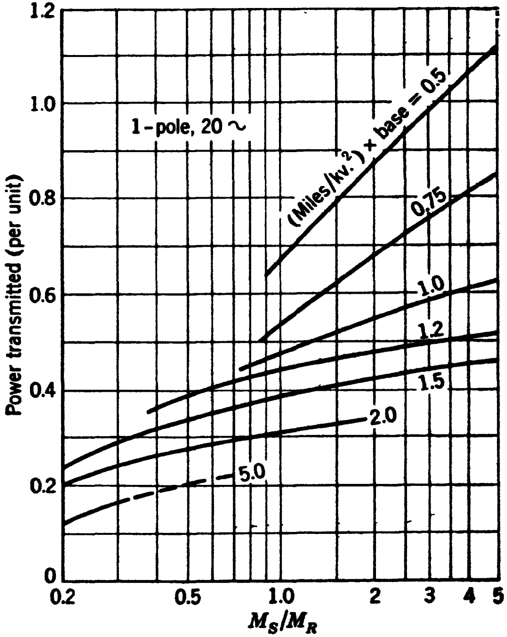


FIG. 33.

FIGS. 30 to 33, inclusive. Transient stability limit for reclosing of a single tie line between two steam-electric power systems for various ratios of sending- to receiving-system inertia. Base equals generating capacity of the receiver system, and per-unit power is referred to this base. Faults are double-line-to-ground, cleared in 0.15 sec. (From discussion of Ref. 24 by H. N. Muller, Jr., by permission) been the common practice to regard a system as satisfactorily stable if it will endure a two-line-to-ground fault at the worst location and with the heaviest load transmitted. On this basis of design, the advantage of single-pole switching over three-pole switching is not as marked as it would be if a more logical basis were used.

A more rational basis of system design would be to make the probability of occurrence of instability lower than some acceptable value (say, once in 10 years). The calculation of the probability of instability would then have to take into account the likelihood of occurrence of each type of fault and the anticipated loads as a function of time of day and time of year. Such calculations become more feasible as our knowledge of the performance of lines of various kinds increases.

It would certainly not be fair to assume that an old, poorly designed line would give as good performance with respect to stability as a modern "lightning-proof" line, just because both systems could withstand two-line-to-ground faults without becoming unstable. Two-line-to-ground and three-phase faults might be much more frequent on the poorly designed line than one-line-to-ground faults were on the well-designed line. On a modern, well-designed line the probability of occurrence of faults of all types is low, and of these the proportion which involves more than one phase is low. Therefore the combined probability of a two-line-to-ground fault occurring on such a line at a time of peak transmission may be very low indeed. The probability of instability of a system of such lines, designed to be stable during one-line-to-ground faults only, may well be lower than the probability of instability on a system of poor lines, designed to be stable during three-phase faults. Under these circumstances it seems reasonable to use the one-line-to-ground fault as the stability criterion for the former system. When the one-line-to-ground criterion is taken, single-pole switching appears very advantageous.

Rapid reclosure versus overhead ground wires, protector tubes, and ground-fault neutralizers. Rapid reclosure is only one of several means for decreasing the probability of loss of synchronism and, more generally, for increasing the reliability of electric-power service. Among the other means of increasing reliability through prevention of faults or through lessening the severity of their effects are overhead ground wires, protector tubes, and ground-fault neutralizers.

Overhead ground wires serve to prevent most flashovers of line insulation by lightning strokes.

Protector tubes serve to extinguish the power arcs which follow flashover of line insulation by lightning.

Grounding of the neutral points through ground-fault neutralizers (Petersen coils), which resonate with the zero-sequence capacitance, prevents line-to-ground faults—which, as already pointed out, comprise about 80% of all faults—from being short circuits and makes two-line-to-ground faults have merely the effect of line-to-line short circuits. Ground-fault neutralizers make transitory line-to-ground faults self-clearing and make possible the continued operation of a power system having a permanent line-to-ground fault until the fault can be located and repaired. They are applicable to cables as well as to open-wire lines.

Overhead ground wires, protector tubes, and ground-fault neutralizers all serve to reduce the number of circuit-breaker operations, but they do not eliminate the need for circuit breakers. Circuit breakers are still essential not only for routine switching but also for clearing some faults. Ground wires and protector tubes prevent or suppress only faults caused by lightning or overvoltage; circuit breakers are still needed to clear faults from other causes. Ground-fault neutralizers neutralize only line-to-ground faults; circuit breakers must clear faults of other types.

The several devices mentioned above should be considered both as alternatives and as supplements to rapid reclosure of circuit breakers, the objective being to secure the highest reliability with the lowest cost.[29, 42]

Some experience obtained in Sweden with rapid reclosure on radial lines of 11 to 44 kv. equipped with resonant neutral grounding shows the value of rapid reclosing to supplement the ground-fault neutralizer.[46] The resonant neutral grounding, of course, eliminated most of the line-to-ground faults without opening any circuit breakers. Out of 1,084 disturbances which did open circuit breakers, high-speed reclosure was successful in 885 cases (82%), 3-min. reclosure was successful in 154 of the remaining cases (14%), and lockout occurred in only 45 cases (4%).

A complete discussion of the various protective devices is beyond the scope of this book.

Rapid closing of bus-tie switches.[31] We have already seen how stability is aided by the rapid opening of circuit breakers in order to clear a fault, and is further helped if the rapid opening is followed by rapid reclosing. It is also possible to improve stability by the rapid closing of a normally open switch—for example, of a bus-tie switch on a double-circuit line. This possibility will be illustrated by the results of calculations made on the particular power system shown in Fig. 34.

Here power is being transmitted over a double-circuit line from a hydroelectric station to a large receiving system. Figure 35 shows the effect of high-voltage bussing at both ends of the line on the stability of the system when a two-line-to-ground fault occurs near the sending end of one circuit and is cleared by simultaneous opening of the breakers at both ends of that circuit. Stability limit is plotted as a function

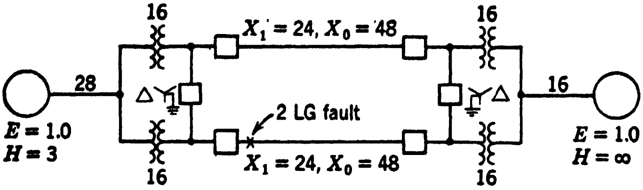


FIG. 34. Power system used to illustrate the effect of high-voltage bussing on stability. Reactances are shown in per cent.

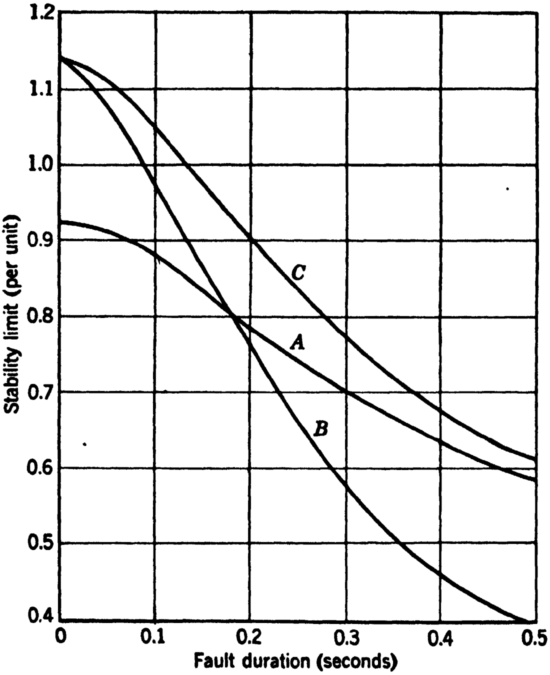


FIG. 35. Effect of the rapid closing of bus-tie switches on the stability of the power system of Fig. 34. (From Ref. 31 by permission)

of fault duration. Curve *B* is for the transmission system with high-voltage busses; curve *A*, for the system without high-voltage busses. High-voltage bussing is detrimental to stability as long as the fault is on the line, because the fault then pulls down the voltage of both circuits and thus impairs their capacity to transfer power. After clearing of the fault, however, the bussing is beneficial, because it lowers the reactance between generators by connecting two banks of transformers in parallel at each end of the remaining transmission circuit. With slow clearing of the fault, the detrimental effect of bussing during the fault predominates over the beneficial effect after clearing the fault. With rapid clearing, the opposite is true. As a result, curve *A* is above curve *B* at long fault durations, and *B* is above *A* at short durations. The curves cross at a fault duration of about 0.15 sec. (9 cycles), which is the time of clearing if standard 8-cycle circuit breakers and 1-cycle relays are used.

The thought naturally occurs: Inasmuch as high-voltage bussing is detrimental during the fault but beneficial after the fault, why not use bus-tie switches which are normally open but which close simultaneously with the opening of the breakers which disconnect the faulty line? The same protective relays which open each line breaker could be used to close the nearby bus-tie switch.

When such switching is used on the power system of Fig. 34, the calculated stability limit as a function of fault duration is as shown by curve *C* of Fig. 35. At zero fault duration curve *C* coincides with curve *B*, because conditions during the fault are immaterial and conditions after clearing are the same for both curves (the bus ties are closed). At long fault durations curve *C* closely approaches curve *A*, because conditions during the fault are the same for these two curves (the bus ties are open) and conditions after clearing are unimportant. Elsewhere curve *C* is above both curves *A* and *B*, because the power limit has been raised through closing the bus-tie switches simultaneously with the opening of the line breakers. The increase in stability limit over that obtainable with the higher of curves *A* and *B* is greatest at the intersection of these two curves, which is in the neighborhood of the clearing times afforded by modern high-speed relays and breakers. With 0.15-sec. (9-cycle) clearing, the stability limit is increased from 0.87 to 0.98—an increase of 12 or 13% over the first-named value. With 0.10-sec. (6-cycle) clearing, the stability limit is increased from 0.98 to 1.05—an increase of 7%. *The improvement attainable through rapid closing of bus-tie switches in conjunction with 8-cycle breakers is just equal in this case to the improvement attainable through replacing 8-cycle breakers with 5-cycle breakers.*

Calculations on this particular power system show that the increase of stability limit due to rapid closing of bus-tie switches is three or four times as great as the increase obtainable through rapid reclosing of the line breakers if the clearing time is 0.10 or 0.15 sec. and the dead time 0.25 sec. The system is of a type for which, it has already been pointed out, reclosure is of little value (low-inertia hydroelectric generators and a double-circuit line). Rapid closing of the bus-tie switches has the further advantage that it is effective even with permanent faults, whereas rapid reclosing is beneficial only with transitory faults and is detrimental with permanent faults. For this reason, rapid closing of bus ties could be applied to underground-cable lines.

Rapid closing of bus-tie switches can be employed in conjunction with sequential clearing of faults. Generally, however, changing from sequential to simultaneous clearing gives much more improvement than does the addition of rapid-closing tie switches.

The principle of rapid closing of a normally open switch simultaneously with the clearing of a fault in order to improve stability is not limited to bus-tie switches on double-circuit lines, but is applicable to any switch which, when open and closed, yields two curves which cross like A and B in Fig. 35.

REFERENCES

1. E. W. Robinson and S. J. Spurgeon, "Automatic Reclosing of High-Voltage Circuits," *A.I.E.E. Trans.*, vol. 48, pp. 981–7, July, 1929. Disc., p. 987.

2. S. B. Griscom and J. J. Torok, "Keeping the Line in Service by Rapid Reclosing," *Elec. Jour.*, vol. 30, pp. 201–4, May, 1933.

3. A. E. Anderson, "Automatic Reclosing of Oil Circuit Breakers," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 53, pp. 48–53, January, 1934. Disc., pp. 466–7, March; pp. 614–6, April.

4. J. T. Logan, "Faster Reclosing Breakers Needed," *Elec. Wld.*, vol. 103, pp. 571–2, April 21, 1934.

5. W. M. Emmons, "Immediate Automatic Reclosing of Circuit Breakers," *Elec. Jour.*, vol. 32, pp. 114–8, March, 1935.

6. D. C. Prince and A. E. Anderson, "Immediate Initial Reclosure of Oil Circuit Breakers," *Gen. Elec. Rev.*, vol. 38, pp. 258–62, June, 1935.

7. J. T. Johnson, Jr., and J. W. Graff, "Immediate Reclosure of 110-Kv. Breakers," *Elec. Wld.*, vol. 105, pp. 21–3 (2101–3), August 31, 1935.

8. J. T. Johnson, Jr., and J. W. Graff, "Results with Quick Reclosure of 110-Kv. Breakers," *Elec. Wld.*, vol. 105, pp. 38–40 (2214–6), September 14, 1935.

9. R. E. Pierce, R. E. Powers, E. C. Stewart, and G. E. Heberlein, "Carrier Relaying and Rapid Reclosing at 110 Kv," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 55, pp. 1120–9, October, 1936.

10. Philip Sporn and D. C. Prince, "Ultrahigh-Speed Reclosing of High-voltage Transmission Lines," *A.I.E.E. Trans.*, vol. 56, pp. 81–90, 100, January, 1937. Disc., pp. 1033–6, August.

11. A. C. Schwager, "The Ultrahigh-Speed Reclosing Expulsion Oil Circuit

Breaker," *Elec. Eng.* (*A.I.E.E. Trans.*), vol. 56, pp. 968–70, August, 1937. Disc., pp. 1514–5.

12. W. Kaufmann, "Die Löschung von Lichtbogenkurzschlüssen durch kurzzeitiges Abschalten (Extinction of Short-Circuit Arcs by Removing Voltage for Short Times)," *E.T.Z.* (Berlin), vol. 60, pp. 241–5, March 2, 1939.

13. Philip Sporn and C. A. Muller, "Experience with Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines," *A.I.E.E. Trans.*, vol. 58, pp. 625–31, December, 1939. Disc., pp. 631–6.

14. Philip Sporn and C. A. Muller, "Five Years' Experience with Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines," *A.I.E.E. Trans.*, vol. 60, pp. 241–6, May, 1941. Disc., pp. 690–4.

15. J. T. Logan and John H. Miles, "Factors Contributing to Improving Electric Service by Means of High-Speed Switching and Utilization of Stored Energy," *A.I.E.E. Trans.*, vol. 60, pp. 1012–6, December, 1941. Disc., pp. 1407–8.

16. S. L. Goldsborough and A. W. Hill, "Relays and Breakers for High-Speed Single-Pole Tripping and Reclosing," *A.I.E.E. Trans.*, vol. 61, pp. 77–81, February, 1942. Disc., p. 429.

17. J. J. Trainor, J. E. Hobson, and H. N. Muller, Jr., "High-Speed Single-Pole Reclosing," *A.I.E.E. Trans.*, vol. 61, pp. 81–7, February, 1942. Disc., pp. 422–3.

18. J. E. Hobson, "High-Speed Reclosing," *Proc. Midwest Power Conference*, vol. 5, pp. 156–64, 1942.

19. S. B. Crary, L. F. Kennedy, and C. A. Woodrow, "Analysis of the Application of High-Speed Reclosing Breakers to Transmission Systems," *A.I.E.E. Trans.*, vol. 61, pp. 339–48, June, 1942. Includes an appendix by H. A. Peterson. Disc., pp. 423–4.

20. R. C. Cunningham and A. W. Hill, "A Compressed-Air Operating Mechanism for Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 61, pp. 695–8, September, 1942. Disc., pp. 1019–20.

21. C. F. Wagner and G. D. McCann, "Lightning Phenomena," Chap. 12 of *Electrical Transmission and Distribution Reference Book* by Central Station Engineers of the Westinghouse Electric & Manufacturing Co., East Pittsburgh, 1st edition, 1942; 3rd edition, 1944.

22. A. C. Schwager, "High Speed Oil Circuit Breakers," a paper presented at the Missouri Valley Electric Association, April 28–30, 1943.

23. A. W. Hill and W. M. Leeds, "High-Voltage Oil Circuit Breakers for Rapid Reclosing Duty," *A.I.E.E. Trans.*, vol. 63, pp. 113–8, March, 1944. Disc., pp. 452–3.

24. W. W. Parker and H. A. Travers, "Reclosing of Single Tie Lines between Systems," *A.I.E.E. Trans.*, vol. 63, pp. 119–22, March, 1944. Disc., pp. 470–2.

25. J. J. Trainor and H. N. Muller, Jr., "H.V. Interconnection Made Reliable by Single Pole Switching," *Power Plant Eng.*, vol. 48, no. 6, pp. 77–79, 138, and 140, June, 1944.

26. L. J. Linde and E. B. Rietz, "A Pneumatic Mechanism for Outdoor Oil Circuit Breakers," *A.I.E.E. Trans.*, vol. 63, pp. 543–6, July, 1944. Disc., pp. 1428–9.

27. W. A. Derr, "Single-Pole Reclosure Holds Stability and Stresses," *Elec. Wld.*, vol. 122, no. 14, pp. 68–9, September 30, 1944.

28. A. C. Schwager, "Tests of 230-Kv. High-Speed Reclosing Oil Circuit

Breaker," *A.I.E.E. Trans.*, vol. 63, pp. 784–8, November, 1944. Disc., pp. 1468–71.

29. H. R. Vaughan, "Pros and Cons of Fast Reclosure of Transmission," *Elec. Wld.*, vol. 122, no. 26, pp. 66–8, December 23, 1944.

30. *American Standards for Alternating-Current Power Circuit Breakers*, New York, American Standards Association, 1945.

31. Edward W. Kimbark, "Improving Stability by Rapid Closing of Bus-Tie Switches," *A.I.E.E. Trans.*, vol. 64, pp. 61–4, February, 1945. Disc., pp. 456–7.

32. G. D. McCann, C. E. Warren, and H. E. Criner, "Determination of Transient Shaft Torques in Turbine Generators by Means of the Electrical-Mechanical Analogy," *A.I.E.E. Trans.*, vol. 64, pp. 51–6, February, 1945. Disc., pp. 492–3.

33. H. S. Kirschbaum, "Transient Electrical Torques of Turbine Generators during Short Circuits and Synchronizing," *A.I.E.E. Trans.*, vol. 64, pp. 65–70, February, 1945. Disc., pp. 492–3.

34. H. N. Muller, Jr., and W. W. Parker, "Reclosing Single-Circuit Tie Lines," *Westinghouse Engineer*, vol. 5, pp. 60–3, March, 1945.

35. Philip Sporn and C. A. Muller, "Nine Years' Experience with Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines," *A.I.E.E. Trans.*, vol. 64, pp. 225–8, May, 1945. Disc., pp. 445–6.

36. I. T. Knight, "Operating Experience with Single-Pole Switching," *A.I.E.E. Miscellaneous Paper* 46-147, May, 1946.

37. C. M. Lytle and J. S. Palmer, "Single-Pole Switching Proves Best for 66-Kv Interconnection," *Elec. Light and Power*, vol. 24, no. 8, pp. 54–7, August, 1946.

38. Philip Sporn and J. H. Kinghorn, "Ultra-High Speed Reclosing Demonstrates Its Value," *C.I.G.R.E.*, report 106, 1946.

39. Hans Thommen, "Problems Connected with the Rupturing of A.C. Currents at Very High Voltages up to 400 Kv," *C.I.G.R.E.*, report 109, 1946.

40. A. Parrini, "Results of Several Years Operation of a High Voltage Supply System Fitted for High Speed Reclosing of the Line Circuit-Breakers," *C.I.G.R.E.*, report 139, 1946.

41. A. Perrin and L. Roche, "Circuit-Breakers and Selective Protective Systems for Ultra-High-Speed Reclosure in Extra-High-Voltage Networks," *C.I.G.R.E.*, report 141, 1946.

42. J. J. Trainor and C. E. Parks, "Experience with Single-Pole Relaying and Reclosing on a Large 132-Kv System," *A.I.E.E. Trans.*, vol. 66, pp. 405–11, 1947. Disc., pp. 411–3.

43. Kenneth M. Reardon, "Service Restoration with Automatic Air-Break Switches," *A.I.E.E. Trans.*, vol. 67, part I, pp. 64–71, 1948. Disc., pp. 71–2.

44. J. W. Batchelor, D. L. Whitehead, and J. S. Williams, "Transient Shaft Torques in Turbine Generators Produced by Transmission-Line Reclosing," *A.I.E.E. Trans.*, vol. 67, part I, pp. 159–64, 1948. Disc., pp. 164–5.

45. Alexander Dovjikov and Clifford C. Diemond, "Performance Test of the Allgemeine Elektricitats Gesellschaft Free-Jet Air-Blast 220-Kv 2,500-Megavolt-Ampere Reclosing Circuit Breaker," *A.I.E.E. Trans.*, vol. 67, part I, pp. 295–304, 1948. Disc., pp. 304–6. The reclosing tests are discussed on pp. 299–302.

46. G. Jancke, "Experience in Operation with Automatic Reclosing of Breakers after Line Faults," *C.I.G.R.E.*, report 306, 1948. Experience in Sweden.

PROBLEMS ON CHAPTER XI

1. Work Example 1 for a three-phase fault.

2. Work Example 2 for a three-phase fault.

3. Work Example 2 for an unsuccessful reclosure on a two-line-to-ground fault.

4. Work Example 2 for a line-to-ground fault.

5. Work Example 1 for a clearing time of 0.15 sec. and a reclosing time of 0.50 sec. after occurrence of the fault.

6. Work Example 2 for a clearing time of 0.15 sec. and a reclosing time of 0.50 sec. after occurrence of the fault.

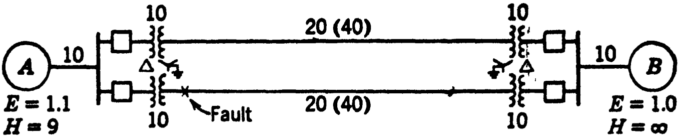


FIG. 36. Power system for Prob. 7. Reactances are given in per cent; values in parentheses are zero-sequence reactances.

7. Find the stability limit of the double-circuit system of Fig. 36 for a two-line-to-ground fault at the sending end of the circuit, cleared in 0.15 sec. with reclosure 0.35 sec. after occurrence of the fault.

8. Find the stability limit of the system of Fig. 2*a* for a two-line-to-ground fault at the sending end of one circuit if single-pole switching is used. The opening time is 0.15 sec. and the reclosing time is 0.35 sec. after the instant of occurrence of the fault. Compare the result with the stability limit found in Example 2 for a three-pole switching.

9. Work Prob. 8 for a line-to-ground fault. If possible, compare the answer with that of Prob. 4.

10. For the system of Fig. 1*a* with a three-phase fault at the sending end, plot a curve of stability limit versus dead time for constant clearing time of 0.10 sec.

11. Work Prob. 10 with a clearing time of 0.15 sec. instead of 0.10 sec.

12. Work Prob. 10 for a two-line-to-ground fault instead of a three-phase fault.

13. For the system of Fig. 1*a* with a three-phase fault at the sending end, plot a curve of stability limit versus clearing time for a constant dead time of 0.20 sec.

14. Work Prob. 13 for a dead time of 0.10 sec. instead of 0.20 sec.

15. Find the stability limit of the system of Fig. 2*a* with a two-line-to-ground fault at the sending end of one circuit cleared sequentially. The breaker at the sending end opens in 0.15 sec.; that at the receiving end, in 0.45 sec.; both reckoned from the instant of fault occurrence.

16. Prove eq. 7.

17. Prove eq. 9.

18. Show that, while one phase wire is open, a phase-selector relay operating on zero- and negative-sequence currents will select the open phase.

19. Show that during a two-line-to-ground fault a phase-selector relay operating on zero- and negative-sequence currents will select the unfaulted phase.

20. Which phase will be selected by the phase-selector relay while two phase wires are open?

21. Work Example 1 with an inertia constant of 3 instead of 9.

22. Work Example 1 with an inertia constant of 20 instead of 9.

INDEX

Admittance setting of mho relay, 94
Air-blast circuit breakers, 5, 16, 34–8
  references on, 59–61
Air circuit breakers, 4–5, 33–8, 41
  references on, 58–61
Air power circuit breakers, *see* Air circuit breakers
Angle circles, 178, 191–2
Angle of maximum torque, 81, 83, 85, 94, 95, 105
Apparatus protection, 130–40
  references on, 151–3
Application of circuit breakers, 46–50
Arc drop, 86
Arc energy, 17
Arc extinction, 16–21
Arc resistance, 91
  effect of, on balance point, 93, 98, 106
Arc theory, references on, 51–2
Attenuation of carrier, 108, 117
Auxiliary switches, 14, 15
Axial-blast air circuit breakers, 35–8

Back-up protection, 67, 70, 79, 89, 101, 107, 112, 118, 120, 140
  reverse, 213–5
  with offset mho element, 96
Baffles, 22–3, 25
Balance point, 79, 88, 89, 91, 93, 94, 98, 99, 129
  effect of generating capacity on, 79, 89
  effect of resistance on, 91, 93, 98, 106
  effect of type of fault on, 94
Balanced-currect relays, 100–1
  effect of swings upon, 172
Beam relay, 74–5, 89, 93
Bias, 74
Bipolar circles, 187–92
Blinders, 173, 201–3, 211
Blocking, of reclosure, 211
  out-of-step, 204–11
Breakers, *see* Circuit breakers
Broken-delta connection, 102–3
Buchholz relay, 137–9
Buffer area, 205–6, 211, 212
Bus faults, 140, 232
Bus protection, 140–3
  references on, 153–4
Bus-tie switches, rapid closing of, 271–4
Bushing current transformers, 11, 32, 76
Bushings, 6, 11, 12, 13, 32
Bussing, high-voltage, effect of, on stability, 271–4
Byrd and Pritchard's method, applications of, 225, 228, 230

Capacitance, effect of, on impedance loci, 192–9
Capacitance potential devices, 76, 114
  references on, 154
Capacitor, coupling, 114–6
Carrier-current channels, 106, 107–8, 114, 116–7, 121
Carrier-current relaying, *see* Carrier-pilot relays
Carrier-current relays, *see* Carrier-pilot relays
Carrier frequencies, 114, 116, 128
Carrier-pilot relaying, *see* Carrier-pilot relays
Carrier-pilot relays, 3, 114–30
  directional comparison, 107–8, 117–23, 128, 129, 169–73
  effect of swings upon, 169–71, 172, 199–213
  out-of-step blocking, 204–11
  phase-comparison, 123–8, 211
  references on, 150–1

Carrier receiver, 114–6, 125–6
Carrier transmitter, 114–6, 125–6
Channels for pilot relaying, 106, 107–8, 114, 116–7
Charging current, interruption of, 19, 26, 38, 46
Circuit breakers, 1–66, 242–7
  air, 4–5, 33–8, 41
    references on, 58–61
  air-blast, 5, 16, 34–8
    references on, 59–61
  application of, 46–50
  classes of, 4
  compressed air, 5, 16, 34–8, 59–61
  contacts of, 7, 9, 12–3, 22–38
  control circuits of, 15–6
    with reclosure, 247–9
  cross-air-blast, 34–5
  De-ion air, 34
  De-ion grid, 26–7, 29, 30–1
    multiflow, 25, 28
  eight-cycle, 3, 39–41
  explosion-chamber, 21–2
  expulsion-chamber, 30, 32
  five-cycle, 3, 24–5, 40
  floor-mounted, 10, 11
  for rapid reclosing, 242–7
  frame-mounted, 8, 9
  free-jet air-blast, 36–8
  high-speed, 3, 21–38
  high-voltage, 5
  impulse, 25–7
  interrupting capacity of, 5, 33, 39–41, 42–3, 47
  interrupting ratings of, 39–45, 47
  interrupting time of, 2–3, 39–41, 44
  low-oil-content, 12, 26, 27, 33
  low-voltage, 4
  Magne-blast, 34
  magnetic-blowout, 5, 34
    references on, 58
  medium-high-voltage, 5
  medium-low-voltage, 5
  multibreak, 24, 26, 29–30
  multi-flow De-ion, 25, 28
  nonoiltight, 10
    interrupting performance of, 45
    standard duty cycle of, 44
  oil, 6–13, 16, 21–33, 39–40
    fire hazard of, 33
Circuit breakers, oil, maintenance of, 33
    modernization of, 33, 58
    references on, 55–8
  oil-blast, 21–5
  oilless, 5, 33–8, 41
  oil-poor, 12, 26, 27, 33
  oiltight, 10
    standard duty cycle of, 44
  opening time of, 3, 43
  operating mechanisms, 10–4
    pneumatic, 14, 244–6
    reclosing, 243–7
    references on, 64
  plain-break, 21
  pneumatic operation of, 14, 34–8, 244–6
  power, 5
  preferred ratings of, 39–41
  rapid reclosing of, 2, 220–78
  ratings of, 38–45
    references on, 64
  rebuilding of, 3
  reclosing of, 2, 220–78
  reclosing time of, 3, 4, 220, 246–7
  references on, 50–65, 274–6
  resistors on, 30–2, 44, 137
  rotary, 32
  slow-speed, 3
  speeds of, 2–4, 39–41, 44, 220, 246–7
  standards for, 64
  tanks, 7–9, 11–3, 32, 34
  testing of, 45–6
    references on, 62–3
  three-cycle, 3, 26–7, 40
  travel-time curve of, 246
  trip-free, 14–5, 245
  water, 5
    references on, 61
  with auxiliary pistons, 26, 28
Circulating-current pilot-wire relaying, 108–10, 129
Clearing time, 2, 3
Closing coil, 13, 15, 244, 248
Compressed-air circuit breakers, 5, 16, 34–8
  references on, 59–61
Connections of directional relays, 82–6
Contactor switch, 120

Contacts, circuit breaker, 7, 9, 12–3, 22–38
  relay, coordination of, 87
Continuous current, rated, 39–41, 42
Control circuits of circuit breakers, 15–6
  with reclosure, 247–9
Coordination, of contacts, high-speed directional overcurrent relays, 87
  of ground relays, 103–4
  of relay settings, 78
Coupling capacitors, 114–6
Cross-blast air circuit breakers, 34–5
Current, fault, calculation of, 46–50, 64
  rated continuous, 39–41, 42
  rated four-second, 39–41, 44
  rated interrupting, 39–41, 42
  rated latching, 45
  rated making, 45
  rated maximum interrupting, 39–41, 43
  rated momentary, 39–41, 44
  rated short-time, 39–41, 44
Current-balance relays, 100–1
  effect of swings upon, 172
Current comparison, 106–14, 129, 172
Current-interrupting capacity, 39–41, 42–3
Current locus, 166–9
Current transformers, 75–6, 104, 109, 111, 132, 134, 141–2
  bushing type, 11, 32, 76
  for bus protection, 141–2
  references on, 154–5
  saturation of, 142
Current-voltage product relays, 105
Currents, delta, 76, 86, 98–9
  relay, 75–6

Dead time, *see* Deionization time
Decrement of short-circuit current, 43, 47
De-energization time, *see* Deionization time
De-ion air circuit breakers, 34
De-ion grid, 26–7, 29, 30–1
  multi-flow, 25, 28
Deionization of arc, in circuit breaker, 16
Deionization of arc, in fault, effect of resistor current on, 44
Deionization time, 222, 237–42, 246, 254–7, 261–4
  for single-pole switching, 239–42
Delay, *see* Time delay
Delta currents, 76
  used with directional relay, 86
  used with distance relays, 98–9
Derating factor, 44, 243
Desensitization, initial, of differential relays, 135–6
Differential relays, 131–7, 141–2
Directional comparison, 107–8, 117–23, 128, 129, 169–73
Directional control, 86–8, 97
Directional overcurrent relays, 81–3, 86–8
  ground, 102–3
Directional relays, 80–8, 95
  connections of, 82–6
  negative-sequence, 104–5
  polyphase, 82, 86
  references on, 146
Directional starting element, 93–5
Disk, 73
Distance relays, 88–99
  bus, 142–3
  carrier-pilot, 117–23
  comparative reach of, 200
  effect of swings upon, 160–6, 199–204
  ground, 105–6
  on tapped lines, 128–9
  references on, 146–8
Double-circuit line, effect of reclosing on transient stability of, 224–5, 228–31, 255–7
Duty cycle, 39–41, 43–4

Electronic relays, 75, 125–7
  references on, 156
End zone, 71, 72, 100, 118, 129
Equal-area criterion, 223–5, 227–8, 231, 237
Explosion chamber, 21, 22
Expulsion chambers, 30, 32

False tripping, due to induced current, 104

- False tripping, due to inequality of current-transformer ratios, 109, 111, 132, 142
  - due to inrush current, 135
  - due to residual magnetism, 101
  - due to reversal of power, 86–7
  - due to swings, 159
    - prevention of, 199–204
- Fault area, 95, 170, 173, 201
- Fault bus, 143
- Fault clearing, 1–157
  - desirability of rapid, 1
- Fault currents, simplified calculation of, 46–50
  - references, 64
- Fault detector, 107, 117, 125–6
- Fault-impedance locus, 162, 169, 193–4, 197
- Fault resistance, 91
  - effect of, on balance point, 91, 93, 98, 106
    - on fault current, 102
- Faults, bus, 140, 232
  - percentage of one-line-to-ground, 233
  - permanent, 220, 222, 231–2
  - transformer, 138–9
  - transitory, 220
- Field, loss of, 216
- Filters, 105, 113, 123–6, 251–2
- Four-second current, rated, 39–41, 44
- Free-jet air circuit breaker, 36–8
- Frequencies, carrier, 114, 116, 128
- Frequency, rated, 41, 42

- Gas-actuated relay, 137–8
- General circuit constants, 194
- Generating capacity, effect of, on balance point, 79, 89
- Generator protection, 131–3
  - out-of-step, 215–7
- Ground-fault neutralizers, 270–1
- Ground-fault relaying, *see* Ground relays
- Ground preference, 119–21
- Ground relays, 69, 101–6, 130
  - carrier-pilot, 118–23, 128
  - current-voltage product, 105
  - directional overcurrent, 102–3
  - distance, 105–6
  - effect of swings upon, 172
- Ground relays, negative-sequence, 104–5
  - overcurrent, 101–4
  - pilot-wire, 107, 112
  - polarization of, 102, 105
  - references on, 148–9
- Ground wires, 270–1
- Grounding switch, 140

- Half-pole test, 46
- Harmonic restraint, 136, 142
- High-speed circuit breakers, 3, 21–38
- High-speed reclosing, *see* Reclosing
- High-speed relays, 3, 69, 72
  - differential, 135–7, 139, 140–2
  - distance, 88–99, 117–23, 128–9, 130
    - ground, 105–6
  - overcurrent, 78–80
    - ground, 104
- Hinged-armature relays, 75
- Hydroelectric system, stability of, with reclosing, 262–4

- Impedance, rate of change of, 205, 211
  - seen by relays, 95–7, 160–6, 168–215
    - on unfaulted phases, 180–4, 186, 204
- Impedance chart, 174–92
- Impedance loci, *see* Impedance plane
- Impedance plane, 95, 97, 160–6, 168–215
- Impedance relays, 74, 88–91, 95
  - bus, 142–3
  - carrier-pilot, 118–21
  - effect of swings upon, 160–6, 169–172, 197, 200
  - modified, 97–8, 200, 203, 212
  - out-of-step blocking, 205–10
- Impulse circuit breaker, 25–7
- Indirect tests, 46
- Induced current, zero-sequence, 104
- Induction-cylinder relays, 74, 92–3, 96–7
- Induction-disk relays, 72–4
- Inertia constant, effect of, on success of reclosure, 262, 268–9
- Inrush, 135, 137
- Instrument transformers, 75–6; *see also* Current transformers
  - references on, 154–5

Insulating transformers for pilot wires, 111, 112, 113
Interrupter, air-blast, 36, 38
  multi-flow De-ion grid, 25, 28
  oil-blast, 21–5
  self-generated pressure type, 21
Interrupting capacity, 5, 33, 39–41, 42–3
  calculation of required, 47
Interrupting current, calculation of required, 47
  rated, 39–41, 42
  rated maximum, 39–41, 43
Interrupting kva., rated, 39–41, 43
Interrupting performance, 44–5
Interrupting ratings, 39–45, 47
Interrupting time, 2–3, 33, 39–41, 44

Kva., rated interrupting, 39–41, 43
Kva. interrupting capacity, 39–41, 43

Latch checking, 247–8
Latching current, rated, 45
Lightning, multiple, 222, 242
Line protection, 69–130
  references on, 144–51
  summary of good practice, 130
Line relays, 69
Line trap, 115–7
Linear coupler, 142
Long lines, 171–2, 192–9, 202–3, 210–1, 213–5
Loop, protection of, 81–2
Loss-of-field protection, 216
Loss of synchronism, *see* Out-of-step...

Machines, protection of, 131–3
  out-of-step, 215–7
Magne-blast circuit breaker, 34
Magnet, driving, 73
  permanent, 73
Magnetic blowout, 5, 34, 58
Magnetizing current, inrush of, 135, 137
Magnitude circles, 177, 190–1
Maintenance of oil circuit breakers, 33
Making current, rated, 45
Margin, 101
Master oscillator, 114–6, 119, 120, 123, 124
Maximum torque, angle of, 81, 83, 85, 94, 95, 105
Mechanisms for circuit breakers, 10–4
  pneumatic, 14, 244–6
  reclosing, 243–7
  references on, 64
Memory action, 86, 94, 97
Mho carrier relaying, 122–3, 124
Mho relay, 93, 96–7, 200–2, 205–6
  carrier, 122–3, 124
  offset, 96–7, 122, 205–6, 210
  reversed, 122, 215
Modernization of oil circuit breakers, 33
Modified impedance relays, 97–8, 200, 203, 212
Momentary current, calculation of required, 48
  rated, 39–41, 44
Multibreak circuit breakers, 24, 26, 29–30
Multi-flow De-ion grid interrupter, 25, 28
Multimachine system, 173
Multiterminal lines, 116, 117, 128–9
Mutual impedance of lines, effect of, on ground relays, 104, 106
Mva. interrupting capacity, 39–41, 43

Negative-sequence power, 104
Negative-sequence relays, 104–5
Neutral current for polarizing ground relays, 102
Ninety-degree connection, 83–6

Offset mho relay, 96–7, 122, 205–6, 210
Ohm relays, 92
  as blinders, 201–2
  for out-of-step tripping, 213
Oil, deterioration and purification of, 33
  handling of, 34
Oil-blast circuit breakers, 21–5
Oil circuit breakers, *see* Circuit breakers, oil
Oil-poor circuit breakers, 12, 26, 27, 33
Oilless circuit breakers, 5, 33–8, 41
Oiltight circuit breakers, 10
  standard duty cycle of, 44
Opening time, 3, 43

Operating mechanisms, 10–4
  pneumatic, 14, 244–6
  reclosing, 243–7
  references on, 64
  solenoid, 13
  spring-actuated, 243–4
Opposed-voltage pilot-wire relaying, 110–1, 129
Oscillator, 114–6, 119, 120, 123, 124
Out-of-step blocking, 204–11
  Type GCY carrier-pilot relays, 210
  Type HZ carrier-pilot relays, 207–10
Out-of-step operation, effect of, on relays, 128, 158–99, 204–13, 215–7
Out-of-step protection of machines, 215–7
Out-of-step tripping relays, 211–3
Overcurrent relays, 76–82, 86–8, 128, 132, 140
  directional, 81–3, 86–8
    ground, 102–3
  effect of swings upon, 166–8
  ground, 101–4
  high-speed, 78–9
    ground, 104
  settings of, 78
Overload protection of transformers, 140
Overreach, transient, 96–7

Parallel lines, protection of, 100–1
Percentage-differential relays, 132–5
Performance, interrupting, 44–5
Petersen coils, 271
Phase comparison, 107–8, 123–8, 172, 211
Phase relays, 69
Phase-selector relays, 250–1
Phase-shift circuit, 92, 93
Pilot relaying, 3, 70, 106–28, 129, 130, 172
Pilot-wire relays, 108–14, 129, 130
  references on, 149
Pilot wires, 106, 112, 114
  faults on, 109, 111
  supervision of, 113
Piston, auxiliary, 26, 28
  in impulse oil circuit breaker, 26
Plunger relays, 75
Pneumatic operation of circuit breakers, 14, 34–8, 244–6
Pneumatically trip-free breakers, 245
Polarization, of directional starting element (mho unit), 94, 97
  of ground relays, 102, 105
Polyphase directional relays, 82, 86
Potential devices, capacitance, 76, 114, 154
Potential transformers, 75–6, 102–5, 128
  auxiliary, 102
  elimination of need for, 128
  number required, 102, 105
Power-angle curves, 223–5, 226–7, 230, 236–7
Power circuit breakers, *see* Circuit breakers
Power limit, *see* Stability
Power relay, 73
Preferred ratings of circuit breakers, 39–41
Pretripping, 45, 46
Prevention of tripping during swings, 199–204
Protection, of busses, 140–3
  of machines, 131–3, 215–7
  of transformers, 133–40
  of transmission lines, 69–130, 144–51
Protective relaying, *see* Relays
Protective relays, *see* Relays
Protector tubes, 270–1

Race between relay contacts, 87–8, 123
Radial system, protection of, 78, 81
Rapid closing of bus-tie switches, 271–4
Rapid reclosing, *see* Reclosing
Rated continuous current, 39–41, 42
Rated four-second current, 39–41, 44
Rated frequency, 41, 42
Rated interrupting current, 39–41, 42
Rated interrupting kva., 39–41, 43
Rated interrupting time, 39–41, 44
Rated latching current, 45
Rated making current, 45
Rated maximum interrupting current, 39–41, 43
Rated momentary current, 39–41, 44
Rated short-time current, 39–41, 44
Rated voltage, 39–42

Ratings of circuit breakers, 38–45
  references on, 64
Ratio-differential relays, 132–5
Reach of distance relays, 89, 91
  comparative, 200
Reactance relays, 91–6, 200
  for bus protection, 142–3
  ground, 106
Reactive-current relays, 216
Receiver, carrier, 114–6, 125–6
Receiver relay, 118–23
Reclosing, 2, 220–78
  blocking of, 211
  circuit breakers for, 242–7
  double-circuit line, 224–5, 228–31, 255–7
  factors affecting feasibility of, 222–3
  manual, 220
  of air-blast circuit breaker, 36, 38
  relays for, 249–53
  single-pole, 232–7, 239–42, 246, 253–70
  single-shot, 220, 222
  statistics on success of, 220, 221, 234, 239, 271
  unsuccessful, 222, 232
  versus other protective methods, 270–1
Reclosing time, 3, 4, 220, 246–7
Reclosure, *see* Reclosing
Recovery voltage, 17–20
  references on, 52–4
Relay currents, 75–6
Relay speed, 2–4, 67, 117, 128
Relay time, 2–4, 67, 117, 128
  versus fault location, curves of, 71
Relay tube, 126
Relay voltages, 75–6
Relaying quantity, 112–3
Relays, back-up, *see* Back-up protection
  balanced current, 100–1, 172
  beam type, 74–5, 89, 93
    reactance, 93
  Buchholz, 137–9
  carrier-current, *see* Carrier-pilot relays
  carrier-pilot, *see* Carrier-pilot relays
  construction of, 72–5
  current, 73; *see also* Relays, overcurrent
Relays, current-balance, 100–1, 172
  current-comparison, 106–14, 129, 172
  current-voltage-product, 105
  differential, 131–7, 141–2
  directional, 80–8, 95
    connections of, 82–6
    negative-sequence, 104–5
    overcurrent, 81–3, 86–8, 102–3
    references on, 146
  directional-comparison, 107–8, 117–23, 128, 129, 169–73
  directional overcurrent, 81–3, 86–8
    ground, 102–3
  distance, 88–99
    bus, 142–3
    carrier-pilot, 117–23
    comparative reach of, 200
    effect of swings upon, 160–6, 199–204
    ground, 105–6
    references on, 146–8
  effect of swings upon, 128, 158–204
  electronic, 75, 125–7, 156
  for rapid reclosing, 249–53
  for selective-pole switching, 251–3
  for single-pole switching, 249–53
  gas-actuated, 137–9
  ground, *see* Ground relays
  harmonic restraint, 136, 142
  high-speed, 3, 69, 72
  high-speed differential, 135–7, 139, 140–2
  high-speed distance, 88–99, 117–23, 128–9, 130
    ground, 105–6
  high-speed overcurrent, 78–80
    ground, 104
  hinged-armature, 75
  impedance, *see* Impedance relays
  induction-cylinder, 74, 92–3, 96–7
  induction-disk, 72–4
  line, 69
  mho, 93, 96–7, 200–2, 205–6, 210, 215
  mho carrier, 122–3, 124
  modified impedance, 97–8, 200, 203, 212
  negative-sequence, 104–5
  ohm, 92, 201–2, 213
  operation of, during swings and out of step, 128, 158–204

Relays, out-of-step tripping, 211–3
  overcurrent, 76–83, 86–8, 101–4, 128, 132, 140, 166–8
  percentage-differential, 132–5
  phase, 69
  phase-comparison, 107–8, 123–8, 172, 211
  phase-selector, 250–1
  pilot, 3, 70, 106–28, 129, 130, 172
  pilot-wire, 108–14, 129, 130
    references on, 149
  plunger, 75
  polyphase directional, 82, 86
  power, 73
  protective, 67–219, 249–53
  ratio-differential, 132–5
  reactance, 91–6, 200
    bus, 142–3
    ground, 106
  reactive-current, 216
  receiver, 118–23
  requirements of, 67–9
  selectivity of, 1–2, 67, 77–8, 80–2, 103–4
  slow-speed, 3, 72, 76–8, 88
  solenoid, 75
  speeds of, 2–4, 67, 117, 128
  thermal, 140
  Type CA, 132
  Type CO, 77
  Type CPD, 113
  Type CZ, 88
  Type GCX, 74, 92–3, 95, 118, 122
  Type GCY, 96–7
  Type GCY carrier-pilot, 118, 122–3
    out-of-step blocking, 210
  Type HCB, 112–3
  Type HCZ, 90
  Type HKB, 125–8
  Type HZ, 74, 89–90, 95
  Type HZ carrier-pilot, 118–21
    out-of-step blocking, 207–10
  Type HZM, 98, 118
  Type IAC, 77
  undercurrent, 216
  zero-sequence, 102–4, 112–3
Resistance of arc, 91
  effect of, on balance point, 93, 98, 106
Resistors on circuit breakers, 30–2, 44, 137
Restraining torque, 92, 94
Restraining windings, 111, 113, 119, 132–5, 142
Restraint, 94; *see also* Restraining windings
  harmonic, 136, 142
Restrikes, 19
Reverse back-up protection, 213–5
Reversed mho relay, 122, 215

Saturation of current transformers, 142
Selective-pole switching, 232–7, 239–42, 246, 253–70
  relays for, 251–3
Selectivity, 1–2, 67
  overcurrent ground relays, 103–4
  overcurrent relays, 77–8, 80–2
Separators, 10, 12
Sequential tripping, 72, 100, 129
Settings, reactance relay, 92–3
  relay, 78
  time, 90
Shaded-pole magnet, 73
Shading coil, 73
Short-circuit currents, decrement of, 43, 47
  simplified calculation of, 46–50
    references on, 64
Short lines, protection of, 98
Short-time current, rated, 39–41, 44
Single-circuit line, effect of reclosing on transient stability of, 223–4, 225–8, 231, 232–3, 254, 261–9
Single-line protection, 101
Single-phase directional relays, 82, 86
Single-pole switching, 232–7, 239–42, 246, 253–70
  relays for, 249–53
Single-shot reclosing, 220, 222
Sixty-degree connection, 86
Slow-speed relays, 3, 72
  distance, 88
  overcurrent, 76–8
Solenoid relays, 75
Solenoids for circuit-breaker operation, 13
Speed, of circuit breakers, 2–4, 39–41, 44, 220, 246–7
  of relays, 2–4, 67, 117, 128

- Stability, effect of high-voltage bussing on, 271–4
  - effect of rapid clearing of faults on, 1
  - effect of rapid closing of bus-tie switches on, 271–4
  - effect of rapid reclosure on, 2, 221–37, 253–70
  - effect of sequential fault clearing on, 4
- Standards for circuit breakers, 64
- Starting element, 91, 93–5
- Step-type distance relays, 88–99
- Supervision of pilot wires, 113
- Swing curves, calculation of, 226–8, 230
- Swing-impedance locus, 160–6, 168–215
  - effect of shunt capacitance on, 192–9
  - proof of, 185–92
- Swings, effect of, on relays, 128, 158–204
  - prevention of tripping during, 199–204
- Switchgear, classes of, 4
- Synchronous machines, protection of, 131–3, 215–7

- Tanks, oil-circuit-breaker, 7–9, 11–3, 32, 34
    - live, 8, 12
- Tap-changing transformers, protection of, 135, 139
- Tapped lines, 116, 117, 128–9
- Tapped load, saved by reverse back-up protection, 214
- Testing circuit breakers, 45–6
  - references on, 62–3
- Tests, carrier-current, 121
- Thermal relays, 140
- Thirty-degree connection, 86
- Thyratrons, 125–6
- Time-current characteristic, 77
- Time delay, definite minimum, 77
  - graded, 77–8, 81, 104
  - in current-balance relays, 101
  - inverse, 77
  - kinds of, 70–2
  - need for, 70
- Time settings, graded, 78, 8[illegible]
- Timer, 89, 90, 96, 120–1, [illegible] 12[illegible]
- Torque, angle of maxim[illegible] [illegible]81, [illegible] 85, 94, 95, 105
- Torque, of directional relay, 85
  - of reactance element, 92
  - restraining, 92, 94
- Transferred tripping, 107–8, 140, 172
- Transformer protection, 133–40
- Transformers, current, *see* Current transformers
  - faults in, 138–9
  - included in protective section of line, 91
  - instrument, 75–6; *see also* Current transformers
    - references on, 154–5
  - insulating, for pilot wires, 111–3
  - potential, 75–6, 102–5, 128
  - protection of, 133–40,
  - three-winding, 133–5, 139–40
- Transmission lines, relay protection of, 69–130
    - references on, 144–51
    - summary of good practice, 130
- Transmitter, carrier, 114–6, 125–6
- Trap, line, 115–7
- Travel-time curves, 246
- Trip circuit, for single-pole switching, 252
  - of directional overcurrent relays, 82
  - of impedance relay, 90
    - with out-of-step blocking, 207–10
  - of mho-carrier relays, 122–5
  - of mho relay, 97
    - with blinders, 201
  - of out-of-step tripping relay, 212
  - of overcurrent relays, 80
  - of rectifier relay, 136–7
  - of Type HZ carrier-pilot relays, 119–21
    - with out-of-step blocking, 207–10
  - of Type HZ relay, 90
- Trip coil, 13, 15
- Trip-free circuit breaker, 14–5, 245
- Tripping characteristics, impedance relay, 95
  - mho relay, 97
  - modified impedance relay, 98
  - reactance relay, 95
- Two-machine system, 159
  - results of stability studies with reclosing, 253–67

Two-machine system, swing-impedance locus of, 160–6, 173–99
Two-phase coordinates, 179–80
Type . . . relays, *see* Relays, Type . . .

Undercurrent relay for loss-of-field protection, 216
Undervoltage protection, need for time delay in, 221
Unit operation, 43–4

Vacuum-tube relays, 75, 125–7
Vector diagrams for directional relays, 84
Voltage, low, on directional element, 86
  rated maximum, 42
  rated normal, 39–42
Voltage, rated withstand, 42
  relay, 75–6

Water circuit breakers, 5
  references on, 61
Wind, effect of, on fault resistance, 91

Zero-sequence current, connection of current transformers for, 102–3
Zero-sequence power, blocked by transformer bank, 103–4
  direction of, 102, 104
Zero-sequence relays, 102–4, 112–3
Zero-sequence voltage, connection of potential transformers for, 102–3
Zones of distance relay, 89–90, 93, 95, 96–7, 117–22, 129